AD-A170 220

# FOREIGN TECHNOLOGY DIVISION

NOISES OF KLYSTRON OSCILLATORS OF A SMALL POWER

by

S. A. Kornilov, V. A. Savshinskiy, S. D. Uman

DTIC
ELECTE
JUL 2 8 1986

B

DTIC FILE COPY

# PARTIALLY EDITED MACHINE TRANSLATION

FTD-ID(RS)T-0499-86                                3 July 1986

MICROFICHE NR: FTD-86-C-002001

NOISES OF KLYSTRON OSCILLATORS OF A SMALL POWER

By: S.A. Kornilov, V.A. Savshinskiy, S.D. Uman

English pages: 357

Source: Shumy Klistronnykh Generatorov Maloy Moshchnosti,
        Sovetskoye Radio, Moscow, 1972, pp. 1-200
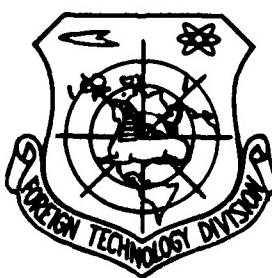
Country of origin: USSR
This document is a machine translation.
Requester: USAMSIC/AIAMS-YDL
Approved for public release; Distribution unlimited.

# MT TRANSLATION CORRECTIONS

As you use this document you may see technical translations which are incorrect or less than optimum. Translation Division personnel will be grateful for any corrections you forward to us. The next page contains blanks for your convenience in recommending better technical translations.

We need three things: the incorrect or poor translation, the correct or improved word or phrase, and the foreign page number.

Example:

Translation # FTD-ID(RS)T-0204-86 (Provided by SIT)

Foreign Page # _____

Incorrect word/phrase: _____

_____

Recommendation: _____

_____

Foreign page numbers occur in the English text and may be found anywhere along the left margin of the page as in this example:

In them occurs the state named "night blindness" - hemeralopia, which, according to the current point of view, is a result of damage of the rod-shaped apparatus of the eye.

Page 51.

However, in recent years it has been shown that with the hereditary pigment degenerations in animals the biochemical changes are observed in all celluar elements of the retina.

Remove the sheet with your recommendations from the translation and forward it to:

SITR/Mr Koolbeck/76538

The dictionary modification process requires from six weeks to six months to accomplish; therefore it will be some time before the results of your recommendations will be evident in translations.

We thank you for your assistance in improving the machine translation product.

i

TRANSLATION # FTD-ID(RS)T-0499-86

Foreign Page # _____

Incorrect word/phrase: _____

_____

Recommendation: _____

_____


Foreign Page # _____

Incorrect word/phrase: _____

_____

Recommendation: _____

_____


Foreign Page # _____

Incorrect word/phrase: _____

_____

Recommendation: _____

_____


Foreign Page # _____

Incorrect word/phrase: _____

_____

Recommendation: _____

_____

Table of Contents

A-1

iii

# U. S. BOARD ON GEOGRAPHIC NAMES TRANSLITERATION SYSTEM

| Block | Italic | Transliteration | Block | Italic | Transliteration |
|-------|--------|-----------------|-------|--------|-----------------|
| А а | *А а* | A, a | Р р | *Р р* | R, r |
| Б б | *Б б* | B, b | С с | *С с* | S, s |
| В в | *В в* | V, v | Т т | *Т т* | T, t |
| Г г | *Г г* | G, g | У у | *У у* | U, u |
| Д д | *Д д* | D, d | Ф ф | *Ф ф* | F, f |
| Е е | *Е е* | Ye, ye; E, e* | Х х | *Х х* | Kh, kh |
| Ж ж | *Ж ж* | Zh, zh | Ц ц | *Ц ц* | Ts, ts |
| З з | *З з* | Z, z | Ч ч | *Ч ч* | Ch, ch |
| И и | *И и* | I, i | Ш ш | *Ш ш* | Sh, sh |
| Й й | *Й й* | Y, y | Щ щ | *Щ щ* | Shch, shch |
| К к | *К к* | K, k | Ъ ъ | *Ъ ъ* | " |
| Л л | *Л л* | L, l | Ы ы | *Ы ы* | Y, y |
| М м | *М м* | M, m | Ь ь | *Ь ь* | ' |
| Н н | *Н н* | N, n | Э э | *Э э* | E, e |
| О о | *О о* | O, o | Ю ю | *Ю ю* | Yu, yu |
| П п | *П п* | P, p | Я я | *Я я* | Ya, ya |

*ye initially, after vowels, and after ъ, ь; e elsewhere.
When written as ё in Russian, transliterate as yё or ё.

## RUSSIAN AND ENGLISH TRIGONOMETRIC FUNCTIONS

| Russian | English | Russian | English | Russian | English |
|---------|---------|---------|---------|---------|---------|
| sin | sin | sh | sinh | arc sh | sinh⁻¹ |
| cos | cos | ch | cosh | arc ch | cosh⁻¹ |
| tg | tan | th | tanh | arc th | tanh⁻¹ |
| ctg | cot | cth | coth | arc cth | coth⁻¹ |
| sec | sec | sch | sech | arc sch | sech⁻¹ |
| cosec | csc | csch | csch | arc csch | csch⁻¹ |

| Russian | English |
|---------|---------|
| rot | curl |
| lg | log |

## GRAPHICS DISCLAIMER

All figures, graphics, tables, equations, etc. merged into this
translation were extracted from the best quality copy available.

# NOISES OF KLYSTRON OSCILLATORS OF A SMALL POWER.

S. A. Kornikov, V. A. Savshinskiy, S. D. Uman

Page 2.

In book noisiness of klystron oscillators of small power
(reflecting and span klystrons) and requirement for their noise
characteristics as a function of application conditions are described.
Is given the noise level reached and the possible ways of its decrease
are discussed.  The chaotic instabilities of amplitude and frequency
as well as regular components in the noise spectra, connected with the
mechanical effects and the ionic processes are examined.  Are informed
about the methods of the measurements of amplitude and frequencies прих
noises.

Book is intended for engineers and scientific workers, who carry
out development and use of klystron oscillators of small power; it
also can be useful for students of advanced courses in
radio-electronic specialties.

7 Tables, 61 Fig., bibl. 105 titles.

Page 3.

Preface.

Noise level of master oscillators and heterodynes in radar devices/equipment is one of most important characteristics, which determine sensitivity of device/equipment and, thereby, technical potential of radio-electronic system as a whole.  Up to now as such generators the reflecting and span klystrons of a small power most extensively are used.

Development of coherent methods of radar advanced special requirements for by klystron oscillator both on noise level in Doppler frequency band and on absence in noise spectrum of different kind of components on account of regular frequency or phase modulation.  In connection with this the development of paths and methods of reduction in the noises of klystron oscillators and connected with this problem investigations of their noise characteristics and the study of the sources of the instability of oscillations/vibrations are at present the main questions about the creation of contemporary klystrons. Interest in these questions on the part of the developers of electronic shf instruments and the designers of radar equipment is sufficiently great.

However, with exception of articles in periodic publications, any generalizing publications, which contain fundamental aspects of problem, virtually are absent.  The available specialized literature

throws light on only the separate questions, connected with noisiness of klystron oscillators.

Known theoretical works, which marked beginning of investigation of fluctuations in reflex klystrons [1], are limited by examination only of separate sources of fluctuations.

FOOTNOTE [1].   I. L.  Bershteyn.  DAN USSR, 1956, Vol. 106, page 453; V. N. Nikon.  "Proceedings of VUZ [     - Institute of Higher Education]", Radiofizik, 1959, Vol. 2, No 6; Ye. N.  Bazarov, M. Ye. Zhabotinskiy.  "radio engineering and electronics", 1959, Vol. 4, No 10 and 1961, Vol. 6, No 1:  A. N.  Masakhov.  Fluctuations in hunting systems. Publishing house "science", 1968.  ENDFOOTNOTE.

Practical there are no works, in which are examined the instabilities of almost periodic character.  The experimental data, available in the periodic literature, are frequently represented in the difficultly comparable form.

Page 4.

Entirely this book is systematic presentation of noisiness of low-power klystron oscillators, including examination of sources of instability of oscillations/vibrations, methods of measuring of noises, and also general questions of application of low-noise klystrons.  According to the intention of the authors the book must be available to both the developers of electrical vacuum instruments and

to creators of radio-electronic equipment, in which are utilized the low-noise klystrons. This created definite difficulties, since the specialists of one group do not frequently have a sufficient preparation in the region of the theory of random processes, and the specialists of another group, as a rule are not familiar with the technological and design problems, which appear during the development of klystrons.

This situation determined style of book, after making it necessary to pay primary attention to physical side of questions examined into loss of strictness of presentation. The mathematical calculations, available in the book, are maximally simplified and they predominantly have illustrative value. The part of the formula is given without the conclusions/outputs. This relates, in particular, to S 2 Chapters 1, where the sources of fluctuations in reflex klystron are examined. The materials of sections of a book, which concern the conditions of applying low-noise klystron oscillators, the methods of noise reduction by radio equipment, the methods of measuring the noises, are presented are schematically introduced for the best understanding of the problems, confronting developments of klystrons.

Readers, who desire more deeply to become acquainted with separate sides of problem in question, will aid references on special literature.

Page 5.

Chapter 1.


OPERATING PRINCIPLES AND NOISINESS OF KLYSTRON OSCILLATORS.

Operating principles, the fundamental parameters and the
characteristics of klystron oscillators.


    Velocity modulation of electronic flux.  The energy conversion of
direct current into the energy of high-frequency field is realized in
the klystrons with the aid of dynamic control of electronic flux.
With is utilized the finiteness of the electron transit time between
the electrodes of instrument.  The electronic flux, formed in the
region of the electron gun, is headed under the effect of the
accelerating voltage/stress into the region of the cavity resonator,
where is concentrated high-frequency electric field, i.e., into the
region of resonator gap.  In the first approximation, all electrons
enter resonator gap with one and the same speed, determined by the
magnitude of the voltage/stress between resonator and cathode of
klystron, and the density of electronic flux to its passage through
the gap remains constant/invariable in the time.  In resonator gap in
the presence of variable/alternating shf voltage the electrons undergo
velocity modulation and they leave gap with different speeds.  The
speed of the electron, which has passed through resonator gap, depends
on the moment/torque of the transit time of gap and is determined by
the expression

$$v = v_0 + v_1 \sin \omega t,$$

where v - speed of the electron, which has passed through resonator gap; $v_0$ - the average speed of electron, determined by direct/constant voltage $V_0$ between cathode and resonator of klystron; $v_1$ - maximum change in the velocity of electron in resonator gap, which corresponds to amplitude U of variable/alternating shf voltage on resonator gap; $\omega$ - the angular frequency of variable/alternating shf voltage.

This expression is correct under condition ( $U/V_0$ )<<1, which is usually fulfilled in low-power generators.

Page 6.

In connection with this the fact that flight/span of electrons through resonator gap are required specific time $t_g$, characterized by transit angle $\theta_g = \omega t_g$, change in velocity of electron in gap, i.e. effectiveness of velocity modulation, it depends on $\theta_g$ The coefficient of the effectiveness of interaction of electrons with shf electric field of resonator (coefficient of electronic interaction) M is connected with the transit angle $\theta_g$ with the following expression:

$$M = \frac{\sin \theta_g/2}{\theta_g/2} \, .$$

The value of a maximum change in the velocity of electron in resonator gap can be determined according to formula $v_1 = v_0 MU/2V_0$. The greater the transit angle $\theta_g$, the less is the gap from the point of view of velocity modulation effective. When $\theta_g = 2\pi$ modulation generally is

absent.  Under the effect of the velocity modulation the electron

stream in the process of further motion becomes heterogeneous on the

density, i.e., velocity modulation is converted into modulation on the

density.  In this case the clusters (packets, groups) of electrons are

formed. The processes of clustering - electron bunching - in the

reflecting and in the span klystrons they are different, although the

difference is not fundamental.  Let us examine the physical picture of

grouping in each of these two types of klystron oscillators.

Grouping in span klystron.  In Fig. 1.1.  schematically

two-cavity span klystron and space-time diagram of electron motion in

the region between the first and second resonators is represented.  On

the diagram the angle of the slope of the lines, equivalent to

electron paths, to the time axis t (angle $\alpha$) is the greater, the

greater the speed of electron motion.  B the region of the gap of

input resonator electrons enter at identical speeds.  In the presence

of shf voltage/stress in the input gap $U\sin\omega t$ occurs modulation of

electrons on the speed and the electrons, which flew the inlet gap at

the different moments of time ($t_1$, $t_2$, $t_3$ on the diagram), they will

move in the space between the input and output gaps with different

speeds.  In this space, called drift space, there are no external

electric fields and electrons move by the inertia.

Speed of electrons, which fly input gap at moment of time $t_1$,

when electrical shf field is equal to zero, does not change.

Page 7.

But the electrons, which fly through the input gap are later, when shf electric field accelerating (moment/torque $t_2$), obtains a velocity increment and will gradually overtake the electrons, which flew gap at moment/torque $t_1$. Accordingly the electrons, which fly through the gap at moment/torque $t_3$, slow down by shf electric field. These electrons will lag behind those previously flown out and gradually converge with the electrons, which flew through the input gap into the range of time from $t_1$ to $t_2$, forming a cluster. The center of this cluster is formed/shaped about the electrons, which flew through the input the gap, when shf voltage on the gap was equal to zero and it was changed from that inhibiting to that accelerating.

So that grouped electronic flux during interaction with field of output resonator would give up to it energy, it is necessary that electronic clusters would enter working gap of output resonator at those moments of time, when shf voltage on gap will be inhibiting. Since the electron transit time in the space of the drift depends on accelerating voltage, then it seems sufficiently to clear that the klystron can generate only within the limits of the specific ranges of values of accelerating voltage of those called the zones of generation.
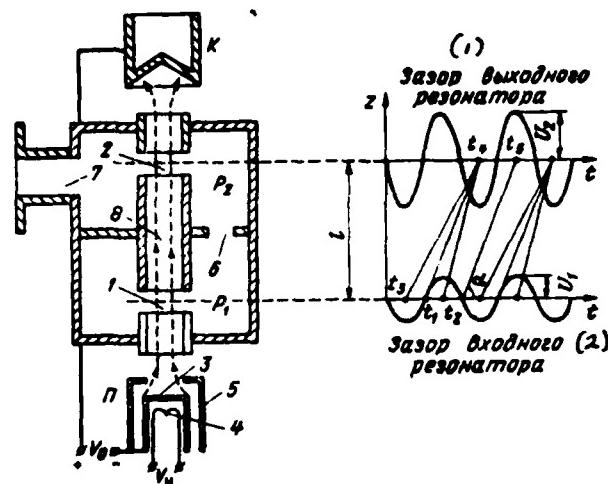
Fig. 1.1. Grouping circuit of electrons in span klystron: $P_1$ - input resonator; $P_2$ - output resonator; $n$ - electron gun; K - collector/receptacle; 1 and 2 - gaps of input and output resonators respectively; 3 - cathode; 4 - heater; 5 - focusing electrode; 6 - opening of connection/communication between resonators; 7 - conclusion/output of shf energy; 8 - drift space; $l$ - length of drift space; $U_1$ and $U_2$ - amplitude of alternating voltages on gaps of input and output resonators respectively; $\alpha$ - angle, whose tangent is proportional to velocity of electrons; t - time; z - distance.
Key: (1). Gap of output resonator. (2). Gap of input resonator.

Page 8.

For maximum energy transfer from electronic flux to field of output resonator bundles of electrons must fall into output gap at moments of time $t_4$ (see diagram in Fig. 1). Based on this condition, it is possible to determine the optimum transit angle of electrons in

drift space $\theta_{\text{онт}}$. in this case necessary to consider possible phase shift $\varphi$ between shf voltage/stress in the output and input gaps, which depends on the device/equipment of feedback between the resonators (diagram Fig. 1 shows the case, when $\varphi=0$)

$$\theta_{\text{онт}} + \varphi = 2\pi \left( N + \frac{3}{4} \right). \qquad (1.1)$$

where N=0, 1, 2, 3, etc.

If length of drift space between centers of input and output gaps is equal to $l$, then expression (1.1) can be recorded as follows:

$$\frac{\omega l}{\sqrt{\dfrac{2e}{m} V_{0\,\text{онт}}}} + \varphi = 2\pi \left( N + \frac{3}{4} \right). \qquad (1.2)$$

From (1.2) values of optimum accelerating voltage $V_{0\,\text{онт}}$ for different numbers of the generating zones N can be obtained.

Grouping in reflex klystron.   Fig. 1.2 schematically depicts reflex klystron and space-time diagram of electron motion in the region between the resonator and the reflector.

In contrast to span klystron, in reflex klystron grouping of electrons occurs in inhibiting electric field.  The greater the speed of the electrons, which fly into the region of the decelerating field between the resonator and the reflector, the greater the path they will pass before the return to resonator gap and the greater the time

will pass between their first and second flight/span through the gap.
Therefore grouping occurs around those electrons, which fly into the
space between the resonator and the reflector, after passing gap at
the moment of the time, when voltage/stress on the gap equal to zero
changes from that accelerating to braking.

Thus, in reflex klystron "slow" electrons seemingly overtake
"rapid".

Page 9.

With the specific voltages/stresses on resonator and the reflector the
electrons will return to resonator gap at such moments of the time,
when field in the gap for the returning electrons is inhibiting.
Consequently, and in reflex klystron there are specific zones of
generation, which depend on the feeding voltages/stresses.  The
optimum transit angle of electrons for the different zones of
generation $\theta_{\text{onт}}$ is determined by the expression

$$\theta_{\text{onт}} = \theta_R + \theta_г = 2\pi\left(N + \frac{3}{4}\right). \qquad (1.3)$$

where N=0, 1, 2, 3...., and $\theta_R$ – transit angle of electrons in the
decelerating field of reflector.

On the basis of condition (1.3), optimum values of feeding
voltages/stresses, which correspond to peak power output in limits of
one or the other zone of generation, can be obtained from expression

$$\frac{\omega l_R}{V_0 + |V_R|}\sqrt{\frac{8m V_0}{e}} + \frac{\omega d}{\sqrt{\frac{2e}{m} V_0}} = 2\pi\left(N + \frac{3}{4}\right). \quad (1.4)$$

where $l_R$ - distance between resonator and reflector; d - gap length of resonator.
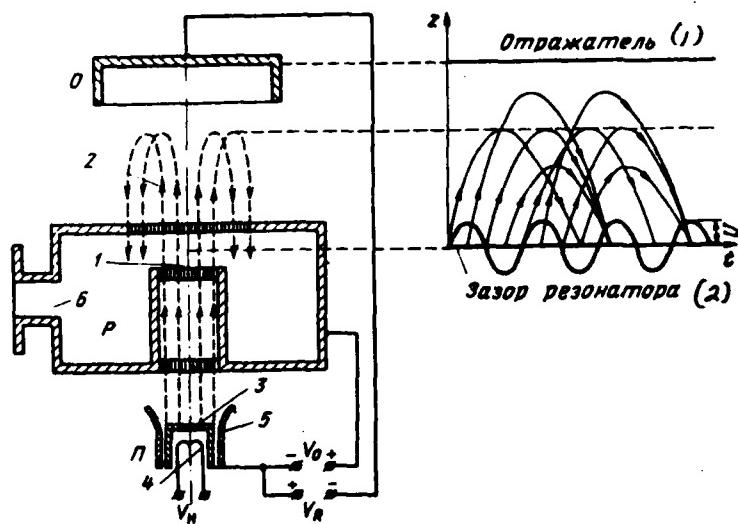
Fig. 1.2.  Grouping circuit of electrons in reflex klystron:  P -

resonator;  п - electron gun; O - reflector; 1 - resonator gap; 2 -

region of grouping; 3 - cathode; 4 - heater; 5 - focusing electrode; 6

- conclusion/output shf energy; U - amplitude of alternationg voltage
on resonator gap; t - time; z - distance.


Key:  (1).  Reflector.  (2).  Resonator gap.

Page 10.

    Process of interaction of modulated on density (grouped) electron

stream with shf field of resonator.  Clusters of electrons, flying

through the gap, induce current in the resonator.  The action of this

current is equivalent to change in the admittance of resonator, in

reference to its gap.  The introduced by electronic flux conductivity

is called electronic conductivity and is equal to the ratio of the

complex amplitude of the fundamental harmonic of the induced current
to the complex amplitude of voltage/stress on the gap:

$$\dot{Y}_e = G_e + jB_e = \frac{I_{\text{и}}}{\dot{U}} = M_2 \frac{I_{\text{конв}}}{\dot{U}} , \qquad (1.5)$$

where $\dot{Y}_e$ - complete electronic conductivity; $G_e, B_e$ - active and
reactive components of electronic conductivity respectively; $I_{\text{конв}}, I_{\text{и}}$ -
complex amplitudes of the fundamental harmonic of convection and
induced currents respectively; $M_2$ - coefficient of electronic
interaction of the output gap (for reflex klystron, in which the
function of input and output gaps they are combined, $M_2 = M_1$).

Amplitude and frequency of steady-state oscillations are
determined from condition of equality of zero sums of hollow
electronic conductivity and admittance of circuit of resonator with
load, in reference to gap:

$$Y_e + Y_{\text{к}} = 0. \qquad (1.6)$$

During the separation of imaginary and real parts (1.6) are obtained
the equations, which determine amplitude and frequency:

$$G_e + G_{\text{к}} = 0, \qquad (1.7)$$
$$B_e + B_{\text{к}} = 0. \qquad (1.8)$$

Since $G_e$ and $B_e$ are functions of transit angle in field of
grouping, then with change in mode of operation of klystron will be
changed power output and oscillation frequency.  A change in the

oscillation frequency of klystron with a change in the voltage/stress on the resonator or voltages/stresses on the reflector is called electronic tuning/adjusting.  From the bunching theory it is known [1, 2], that the complex amplitude of the fundamental harmonic of convection current is expressed for span and reflex klystrons as follows:

$$\dot{I}_{\text{конв}} = 2IJ_1(X)e^{-j\theta}, \qquad (1.9)$$

where X - bunching parameter $(X=MU\theta/2V_0)$; I - operating current in the gap; $J_1$ - function of Bessel of 1 orders.

Page 11.

Complex amplitude of voltage/stress on gap is equal - jU, if instantaneous values are assigned in the form of $U\sin\omega t$.  Then, substituting (1.9) in (1.5), we obtain

$$\dot{Y}_e = G\frac{2J_1(X)}{X}je^{-j\theta}, \qquad (1.10)$$

where

$$G = \frac{M_1 M_2 \theta}{2}\frac{I}{V_0} \text{ - for the span klystron;}$$

$$G = \frac{M^2 \theta}{2}\frac{I}{V_0} \text{ - for reflex klystron.}$$

From expression (1.10) it follows that electronic conductivity of klystron depends on ratio $J_1(X)/X$.  The electronic power of klystron is determined by product $G_e U^2/2$ and therefore $XJ_1(X)$ is proportional,

since $X=MU\theta/2V_0$.  The maximum value of electronic power corresponds to the value of bunching parameter $X=2.4$.  However, due to the effect of losses in the resonator system of klystron the peak power output of klystron oscillator, i.e., the power, isolated in the external load, usually is reached at the smaller values of bunching parameter.  It is possible to show that for obtaining the maximum power in the load the value of load admittance, converted to gap $g_a$, must be close to the conductivity of losses $g_p$.  In this case the optimum value of voltage/stress on the gap is reached at $X\approx1.8$.

In short description presented above of physical processes in klystrons is not examined influence of whole series of factors:  space charge of electronic flux, load, heterogeneities of electric fields, etc.  However, the account of all these factors does not qualitatively change picture and it is necessary only during calculations.  The more detailed illumination of phased processes in the klystrons the reader, can find, for example, in [1, 2].  The effect of different mentioned factors on the noise characteristics of klystron oscillators will be clarified in the subsequent sections.

Page 12.

Fundamental parameters and special feature of work of klystron oscillators.  Such parameters include:

- working frequency band with the mechanical retuning;

- output fluctuating power, isolated in the load;

- electronic-tuning range of frequency, i.e., the band of the generatable frequencies within the limits of one zone of generation corresponding to a change of the feeding voltages/stresses with the decrease of power output up to the specific level (usually to half from the optimum value in the center of the zone of generation). This parameter is especially important for reflex klystrons.

Working frequency band with mechanical retuning is determined in essence by construction/design of resonator system. The range of the mechanical retuning of reflex klystrons for the different types of instruments changes within very wide limits. For the klystrons with the integral cavity, reconstructed by a change in the end capacity/capacitance (gap capacitance of resonator), the range of mechanical retuning is from 5 to 40%. In wide-range reflex klystrons s about by detachable external resonators the range of mechanical retuning it can exceed octave. The mechanical retuning of the frequency of the span klystrons is considerably more complicated than reflecting, and the range of the mechanical retuning of span klystrons does not exceed 2-3%.

Usually to by low-noise klystron oscillator are not presented requirements of guarantee of broad band of mechanical retuning of frequency, which is explained by specific conditions for work of equipment. The need for weakening microphonics for the purpose of lowering the level of vibration noises forces to maximally harden the construction/design of klystrons and to limit the possibility of

displacing the structural elements/cells.  Therefore the most low-noise klystrons, as a rule work either at the fixed/recorded oscillation frequencies or with the mechanical retuning within the small limits ( not more than 10%).

Power output of two-cavity span generator klystrons ranges from several hundred milliwatts to several ten watts, and for reflex klystrons - from several units of milliwatts to 1-2 W.  During the use of klystrons as the heterodynes a sufficient power level does not exceed tens of milliwatts and therefore here predominantly are used reflex klystrons.  From the master oscillators in the amplifier chains/networks hundred milliwatts are required already.  In this case are used both reflecting and span two-cavity klystrons.

Electronic-tuning range in majority of reflecting klystrons composes 0.3-0.5 from fundamental frequency.

Page 13.

This parameter is very important at the use of klystrons in the modes/conditions of frequency modulation and in the diagrams of the automatic frequency control.  Electronic-tuning range is inversely proportional to the quality of the resonator system of klystron. Subsequently it will be shown that the value of frequency noises is inversely proportional to the square of the loaded quality.  Therefore during the creation of the low-noise klystrons they attempt to maximally increase the equivalent quality of resonator system.  In

this case in the most low-noise klystrons electronic tuning/adjusting
virtually is absent.

Sensitivity of frequency to change in voltages/stresses on
resonator or on reflector is closely related to value of
electronic-tuning range.  These parameters can be determined for
reflex klystron from the following expressions:

$$\frac{\partial f}{\partial V_R} \approx \frac{f_0}{2Q_{\text{н}}} \frac{\theta_R}{(V_0 + |V_R|)}, \qquad (1.11)$$

$$\frac{\partial f}{\partial V_0} \approx \frac{f_0}{4Q_{\text{н}}} \frac{\theta_R}{(V_0 + V_R)} \left(1 - \frac{|V_R|}{V_0}\right). \qquad (1.12)$$

Respectively for the two-cavity span klystron

$$\frac{\partial f}{\partial V_0} \approx \frac{f_0}{2Q_{\text{н экв}}} \frac{\theta_{12}}{V_0}, \qquad (1.13)$$

where $\theta_{12}$ -- transit angle of the electrons between the resonators; $Q_{\text{н}}$
- loaded quality of the resonator of reflex klystron; $Q_{\text{н экв}}$  -
equivalent quality of the resonator system of span klystron.

Let us note that expressions (1.11)- ( 1.13) are approximate,
since in them space-charge effect of electronic flux and some other
factors is not considered.  More exact expressions are given, for
example, to [3].

For majority of reflecting heterodyne klystrons sensitivity of
frequency to change in voltage/stress on reflector near center of zone
of generation (this parameter accepted to call slope/transconductance

of electronic tuning/adjusting) comprises in centimeter wavelength range of 0.2-3 MHz/v.  Reflex klystrons with the increased power output, as a rule work on the lower numbers of the zones of generation, i.e., with smaller $\theta_R$, and therefore they have the lower sensitivity of frequency to a change in the feeding voltages/stresses.

Page 14.

This is correct for span klystrons, whose oscillation frequency more weakly depends on voltage/stress on the resonator, the less the number of the zone of oscillations (i.e. the less the value $\theta_{12}$).  For the relatively high- voltage span of klystrons the sensitivity of frequency to a change in the voltage/stress on the resonator composes usually 5-10 kHz/v.

Only fundamental parameters of klystron oscillators above are briefly examined.  For the total characteristic of the performance properties of klystrons there is a complex of the very important parameters, which determine frequency stability and power of the generatable oscillations under different external influences.  Such parameters include for example, the temperature frequency coefficient, which determines the thermostability of klystron, barometric frequency drift, the deviation of frequency and power with the impacts and the vibrations and others.  Since these parameters are not directly connected with the noise characteristics of klystrons, their detailed examination is inexpedient, since it exceeds the scope of the book. Therefore we will be restricted to the following observation.  Some of

the mentioned parameters are determined by the rigidity of construction/design, in connection with which of their magnitude they indirectly characterize the effect of mechanical and acoustic effects on the spectrum of the fluctuations of oscillations of klystron. The corresponding questions will be presented into S 4 this chapter.

In conclusion briefly let us pause at fundamental regimes of work of klystron generators.

Voltage/stress on resonator of contemporary heterodyne reflex klystrons of centimeter wavelength range is 200-400 V with currents of resonator 20-40 mA and power output to 100-200 mW. The modes of operation of reflex klystrons with an increased power output (to 0.5-1.5)   W are characterized by more high voltages on the resonator - to 500- 1000 V. The current of resonator in such klystrons is 50-100 mA usually. Negatively voltage/stress on the reflector in the majority of the cases lies/rests within the limits of 100-500 V. The higher the voltage/stress on the resonator, the less the dense grids (i.e. the more transparent for the electronic flux) can be utilized in the klystron. Therefore with an increase in the voltage/stress usually decreases the interception of grid current and, as it will be shown subsequently, are improved noise characteristics. The lower the electronic conductivity of klystron, the higher-impedance optimum load becomes and the value of the loaded quality of resonator respectively is raised. With by this decreases the sensitivity of frequency to a change in the mode of operation of klystron [cm.   (1.11)- ( 1.13).

All these considerations apply in the same manner both to the reflecting and to the span klystrons.

Page 15.

With parameters and modes of operation of reflecting and span klystrons it is possible to become acquainted, for example, in [4, 5], and also in Chapter 4 this book.

Fig. 1.3 shows appearance of typical low-noise klystrons.

2.   Sources of the chaotic instability of amplitude and frequency of klystron oscillators.

2.1.   Classification of sources of instability and their physical characteristics.

When they speak about steady-state (steady) state of work of generator, then constancy of frequency and amplitude of oscillations is implied.  In actuality even in the steady-state mode/conditions frequency and amplitude of oscillations continuously change under the effect of many internal and external destabilizing factors.  Some of them operate they slowly and affect only the lasting stability of oscillations (change in the ambient temperature, drift of supply voltages, aging the elements of the construction/design of generator). The examination of these sources of instability does not enter into the goals of the book, and we will pay entire attention to such sources, which disrupt the stability of oscillations in time intervals less than 1-10 s.
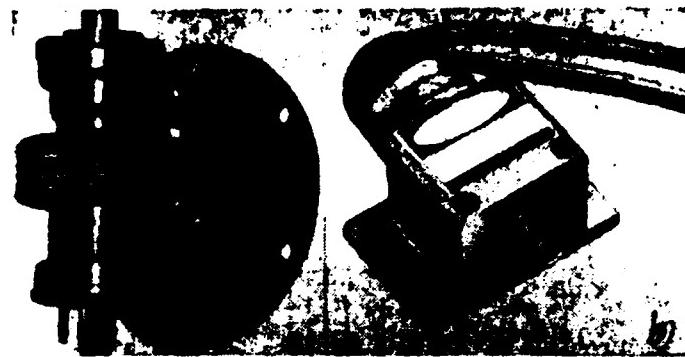
Fig. 1.3.    Appearance of low-noise klystrons:    a) reflecting; b) span.

Page 16.

Short-term instability of oscillations is developed in the form
of rapid changes in amplitude and frequency (divergences of their
instantaneous values from averages).  These changes can be random or
periodic.  Probable deviations (fluctuation) have continuous energy
spectrum, periodic - discrete/digital.  All real processes are not
strictly periodic, only approaching by it to a greater or lesser
extent.  They have continuous spectrum; however, it is concentrated in
the narrow range of frequencies (or in several narrow frequency
ranges).  The processes of this type are called almost periodic.  For
the brevity we will call them subsequently regular, taking into
account their nearness to the purely periodic processes.  Fig.  1.4
shows the form of the spectra of random, purely periodic and almost
periodic (regular) processes.

Regular component instabilities amplitudes and frequencies of electronic generators are caused both by external reasons (pulsation of voltages of supply, focusing/induction, mechanical and acoustic effects) and by internal, connected with complicated physical processes, which take place in region of electron beam of instrument. Nature of regular components will be in detail examined in S 5 present chapters; therefore we will be restricted to the aforesaid and will pass to the examination of the sources of random components of instability (fluctuations) in klystron oscillators.

Shot noise of cathode current. The discreteness carrier of electric charge is the physical cause for the shot fluctuations of cathode current. A quantity of electrons, which leave cathode at the different moments of time, is changed randomly, as a result of which of emission is not constant, but it fluctuates about its average/mean value.
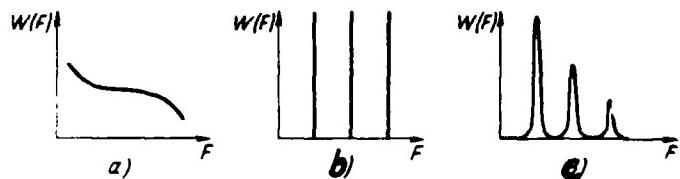
Fig. 1.4.  Energy spectra of random (a), periodic (b) and almost periodic (regular) (c) processes.

Page 17.

If cathode works in the mode/conditions of temperature limitation, then the spectral density of the mean square of the fluctuations of current is given by Schottky's formula (they call also it the formula of complete shot noise):

$$W_{\text{ДР}} = 2eI_s.$$
(1.14)

where e - electron charge; $I_s$ - emission current.

As a rule cathodes of majority of electronic devices are utilized in mode/conditions of limitation of current by space charge.  In this case in immediate proximity of the cathode is accumulated/stored the dense clouds of electrons, whose space charge forms the region of the minimum of potential near the cathode.  Now the strength of current of ray/beam is not equal to emission current, since from the region of the minimum of potential are reflected back/ago to the cathode those electrons, whose initial thermal velocities are insufficient for

overcoming the formed potential threshold.  The mode/conditions of the limitation of current by space charge is always utilized in the klystrons.  The appearance of a region of the minimum of potential significantly changes the noise characteristics of electronic flux. It is not difficult to show that in this mode/conditions the shot noise is suppressed.  In fact, let us assume that a random increase in the emission current occurred.  This will unavoidably increase the density of space charge in the cloud of electrons near the cathode and the depth of the minimum of potential will increase.  As a result a quantity of electrons, capable of overcoming the potential threshold, decreases since for this it is necessary the high initial velocity. Thus, any fluctuation of emission current partially is compensated in the current after the region of the minimum of potential.  The action of the minimum of potential is developed as a kind of negative current feedback.  The spectral density of the mean square of noise current in this case is designed from the formula

$$W_{\text{к}\text{р}} = 2e\,I_{\text{к}}\,\Gamma^2\,(\omega).\qquad (1.15)$$

Here $I_{\text{к}}$ - current of electron beam after the region of the minimum of the potential ( but not emission current as in the case of the mode/conditions of temperature limitation), but $\Gamma^2$ $\omega$) - the coefficient of depression, which considers noise suppression by space charge.  On low frequencies and with the sufficiently large potential of the anode of the electron gun $\Gamma^2$ it is approximated by the formula

$$\Gamma^2 = \frac{9}{4}\,(4 - \pi)\,\frac{k\,T_{\text{к}}}{e\,(V_0 - V_m)}\,,\qquad (1.16)$$

where $V_0$ - potential of the anode of the electron gun; $V_m$ - is the depth of the minimum of potential; $k = 1.38 \cdot 10^{-23}$ J/deg - Boltzmann constant; $T_k$ - absolute temperature of cathode.

Page 18.

Formula (1.16) gives sufficiently good approximation/approach, if potential of anode exceeds several volts. For the oxide cathode, frequently utilized in the klystrons, $T_k \approx 1100°K$   and

$$\Gamma^2 \approx \left(1 - \frac{\pi}{4}\right)\frac{1}{V_0 - V_m} \approx \frac{1}{5V_0} . \qquad (1.17)$$

This expression shows that even in low-voltage reflex klystrons the shot noise at the low frequencies deeply is suppressed; so, with $V_0 = 300$ into the coefficient of depression $\Gamma^2 = 0.6 \cdot 10^{-3}$. Experiment confirms the depression of shot noise by space charge; however, it is not so/such deep, as it follows from the theory. This disagreement can be connected with the disturbance/perturbation of the region of the minimum of potential with electrons, elastic those reflected from the anode. In reflex klystrons to them the electrons, not interepted by grids during the reverse motion from the region of reflector, are added.

Measurements show that for klystron guns with supply voltages of from hundreds of volts to several kilovolts coefficient of depression of shot noise can compose $10^{-2}$ and even it is less.

With increase in frequency suppression of shot noise weakens due

to span effects between cathode and region of minimum of potential (it is developed inertness of cloud of space charge near the cathode). The dependence $\Gamma^2$ on the frequency, designed in an approximate manner, it is shown in Fig. 1.5 [6]. Along the axis of abscissas is plotted relation $\omega/\omega_{pn}$, where $\omega_{pm} = 2\pi^{1/4} \left( \frac{m}{2kT_\kappa} \right)^{1/4} \left( \frac{e J_\kappa}{m\varepsilon_0} \right)^{1/2}$ - natural vibration frequency of electronic plasma into the region of the minimum of the potential (m - mass of electron, $J_\kappa$ - current density, $\epsilon_0$ - dielectric constant of vacuum). In the range of superhigh frequencies $\omega/\omega_{pm}$ it is usually of the order of one; therefore the suppression of shot noise is insignificant. The calculation of the coefficient of depression is carried out for area of beam, directly adjacent the region minimum of potential.
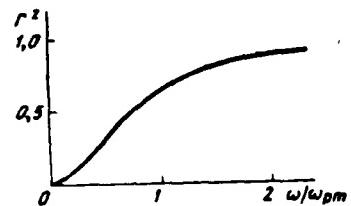
Fig. 1.5.   Dependence of coefficient of depression of shot noise $\Gamma^2$ on frequency.

Page 19.

This is important to remember, since at the superhigh frequencies it cannot be spoken about the noise of the current of ray/beam not at all without specifying the positions of the section in question.  Matter in the fact that in contrast to the low frequencies, at which span effects are weak, at the superhigh frequencies noise current changes its value with the coordinate due to the combined action of span effects and elastic forces of space charge of electrons in the ray/beam.  Later we will pause at the specific character of noise propagation in the electronic flux at the superhigh frequencies in more detail.

Fluctuations of velocity of electrons.  Initial thermal velocities, which escape from the cathode, as is known, they are distributed according to the law of Maxwell:

$$n(v_s) = \frac{m\,n_0}{k\,T_{\kappa}}\, v_s\, e^{-\frac{m v_s^2}{2 k T_k}} . \qquad (1.18)$$

Here $n_o$ - number of electrons, which flew out from the cathode in a certain small time interval, and $n(v_s)$ - number of those of them, which have a speed of escape $v_s$. The average/mean initial velocity is equal to

$$\bar{v} = \left( \frac{\pi k T_k}{2m} \right)^{1/2} . \qquad (1.19)$$

Thus, for oxide cathode $(T_k = 1100°K)$ $\bar{v} = 1.62 \cdot 10^5$ m/s. For the judgment about this value it is useful to express by its equivalent potential $V = \frac{m(\bar{v})^2}{2e} = 0.074$ $V$. This is very small value. Therefore in many instances the electronic flux, accelerated in the gun, is considered one-speed, since against the background of the accelerating potentials into hundred and thousands of volts the velocity spread, measured by the tenth of volt, is negligible. So they enter also during the construction of theory and the calculation of the main parameters of electronic devices, including klystrons. However, during the analysis of noisiness to disregard the multispeed character of the motion of electronic flux is impossible. Matter in the fact that at a sufficient transit angle the difference in the velocities of electrons, even small, will lead to the random grouping of electronic flux, i.e., to the appearance of a supplementary noise current in the ray/beam.

Page 20.

Strict analysis of effect of multispeed electron motion on noisiness of electronic flux is difficult and therefore at present almost always is utilized approximate approach, which consists in the fact that real multispeed flow they replace to one-velocity, but they consider that speed of latter weakly fluctuates in time. The value of these fluctuations can be found from the examination of the average/mean initial velocity of electrons.

If shot effect is absent, then average/mean initial velocity (designed on set of electrons, which left cathode during certain small time interval) does not depend on timing, at which we begin calculation, i.e., it is time-constant value.

Shot effect leads to the fact that quantity of electrons, which possess one or the other speeds, randomly is changed together with random change in total number of electrons from one moment of time to another. Significant is the fact that the random redistribution of a number of electrons, which possess different initial velocities, occurs. Under such conditions the calculation of the average/mean initial velocity at the different moments of time must give somewhat distinguished results: at some moment of time the portion of fast electrons increases and the average/mean initial.velocity grows/rises, after then occurs reverse process and so on. This means that the average/mean initial velocity fluctuates. It is natural that the fluctuations will be preserved also in the accelerated electronic flux, although their value upon the acceleration will change.

Spectral density of mean square of fluctuations of initial velocity for mode/conditions of limitation of current with temperature of cathode is expressed by formula

$$W_v = (4 - \pi)\frac{ekT_\kappa}{mI_s} . \qquad (1.20)$$

With work in mode/conditions of limitation of current by space charge the same formula gives spectral density of fluctuations of speed in minimum of potential, if we replace emission current $I_s$ by current of ray/beam $I_\kappa$ (i.e. to current, formed by electrons, which passed through region of minimum of potential). From (1.20) it follows that the spectral density of the fluctuations of the initial velocity does not depend on frequency.

Ionic noise. With the work of cathode in the mode/conditions of the limitation of current by space charge the ionization of residual gas can cause noise ray/beam. The essence of this phenomenon consists of the following. Forming between anode and cathode of electron gun positive ions are accelerated by electric field available in this region in the direction of cathode.

Page 21.

Falling into the region of the minimum of potential, each ion by the specific time decreases its depth, partially compensating, negative space charge of the cloud of electrons near the cathode. The decrease

of the depth of the minimum of potential causes the flash/burst of electronic current of ray/beam, whose duration is determined by the retention time of positive ion in the region near the cathode. Since the mass of ions many times of more than the mass of electrons, the speed, acquired by the first during their motion to the cathode, is small, which causes a comparatively large duration of the passage of the region of the minimum of potential and the corresponding flash duration of electronic current. Since the ionizing events are random events, the appearance of electronic flashes/bursts of the described type will be random. This means that in the current of ray/beam supplementary component with the continuous spectrum will appear. It was called of ionic noise or noise of ionization. The spectral density of ionic noise is uniform up to frequencies on the order of 10 MHz; at the higher frequencies it rapidly decreases (width of ionic noise spectrum it is determined by the duration of its component electronic bursts).

Ionic noise in triodes is examined in [7, 8]. The results of analysis can be used, also, for the evaluation/estimate of the level of ionic noise in diode electron gun [9]. In this case the spectral density of the mean square of the noise current of ionic origin can be evaluated according to the formula

$$W_I \approx 880 e I_{I\kappa} \sqrt{V_0}.$$   (1.21)

Here $I_{I\kappa}$ — average value of the ion current, which enters the cathode (in the amperes); $V_0$ — accelerating potential (in volts).

Let us rate/estimate specific weight/gravity of ionic noise based on example of typical low-power klystron with parameters:  $V_0$=300 $V$ , $I_\kappa = 0.02$ a.  With the usual vacuum (pressure of residual/remanent of gas on the order of $10^{-7}$ mm rt. st.) the strength of ion current to the cathode is of the order $10^{-7}$ a.  In accordance with formulas (1.15) and (1.17) with the current of ray/beam  $I_\kappa$=0.02 $a$  the spectral density of complete shot noise  $W_{\text{др}} = 2eI_\kappa = 6.4 \cdot 10^{-21}$ a²/Hz.  Depression by space charge ($\Gamma^2 \approx 1/5 \ V_0 = 0.66 \cdot 10^{-3}$) decreases it to value $W_{\text{др}} = 2eI_\kappa \Gamma^2 = 4.2 \cdot 10^{-24}$ a²/Hz.  However, the level of the spectral density of ionic noise on (1.21) is equal to

$$W_j = 880 e I_{j\kappa} \sqrt{V_0} = 2.4 \cdot 10^{-22} \text{ a²/Hz.}$$

Thus, ionic noise can considerably exceed suppressed by space charge shot; however, level of ion noise is noticeably lower than level of complete shot noise.

Page 22.

Noises of current distribution.  The initial velocity of the electron, which escapes from the cathode, has longitudinal and transverse components.  Their values are changed randomly from one electron to the next and therefore the electrons, which flew out from one and the same point on the cathode, move along the random trajectories and at the sufficiently large distance from the cathode they can prove to be at the most varied points of the cross section of ray/beam.  With the interception of the part of the current the indicated fact leads with positive electrode (for example, by grid) to an increase in the noise level in the ray/beam after the section of interception, since a quantity of electrons, which fall by the electrode or passing by it is changed randomly in time. The spectral density of the mean square of this supplementary noise current is designed from the formula

$$W_r = (1 - \beta)\beta \cdot 2eI_\kappa . \qquad (1.22)$$

Here $\beta$ - the coefficient of transmission of grid, which intercepts electrons (it is equal to the ratio of the average/mean current of the ray/beam beyond the grid $I'_\kappa$ - to the average/mean current of the ray/beam before grid $\beta = I'_\kappa / I_\kappa$).

Complete shot noise of current, which passed intercepting electrode, is limiting value of noise of current distribution.  This is evident from formula (1.22):  with $\beta \ll 1$ (almost complete interception of current) $W_r \approx 2eI'_\kappa$  It is necessary to note that current

interception increases the noise level in the ray/beam only in such a case, when the noise level of the current, which is adequate/approach the intercepting electrode, lower than complete shot.

Formula (1.22) shows that spectral noise density of current distribution does not depend on frequency.  This means that current interception can increase the noisiness of ray/beam not only on the low, but also at the superhigh frequencies.  The latter was confirmed the calculations of Beam and experiments [10, 11].

Besides increase in noise current current interception leads to increase in level of fluctuations of speed, since high-speed/high-velocity composition of electronic flux changes randomly upon contact of electrons with different initial velocities with intercepting electrode.

Noises of secondary emission.  The typical distribution of secondary electrons the energies is shown in Fig. 1.6.  The majority of them has an energy, which does not exceed 20 eV, and low speed. The secondary electrons, dislodged/chased from the grids of the high-frequency gap of klystron, for a while move in the gap and they interact with the ac field, as a result of which the supplementary electronic conductivity of gap, which has active and reactive components, appears.

Page 23.

If the current of secondary electrons in the gap fluctuates, then will fluctuate the value of secondary-electron conductivity, which must lead to modulation of amplitude and phase of voltage/stress on the gap. The value of the reactive component secondary-electron conductivity is considerable even with the small current of secondary electrons [12] and therefore its fluctuation they can strongly act on the frequency of generator.

Let us examine noises in current of secondary electrons. If $\sigma$ - secondary-emission coefficient of grid, and $I_1$ - current of the primary electrons, which bombard the conductors of grid, then the current of secondary electrons is equal to $I_2 = I_1 \sigma$.

If primary-electronic current fluctuates ($I_1 = \overline{I_1} + \delta I_1(t)$, then this will cause fluctuations of secondary-electron current, coherent with $\delta I_1(t)$. Furthermore, during the calculation of the fluctuations of secondary-electron current one must take into account that a quantity of secondary electrons, dislodged/chased by one primary, is changed randomly. This leads to the fact that the secondary-emission coefficient, averaged over the surface of the bombarded electrode, fluctuates: $\sigma = \overline{\sigma} + \delta\sigma(t)$, where $\overline{\sigma}$ - average/mean in the time value of secondary-emission coefficient. Taking into account the smallness of fluctuations by comparatively average values, we can find

$$I_2 = \overline{I_2} + \delta I_2 \approx \sigma \overline{I_1} + \sigma \delta I_1 + \overline{I_1} \delta\sigma,$$

whence $\delta I_2 \approx \overline{\sigma} \delta I_1 + \overline{I_1} \delta\sigma$. Components $\delta I_1$ and $\delta\sigma$ are not correlated, so so

their calling processes are independent; therefore the spectral density of the mean square of the fluctuations of secondary-electron current is equal to the sum of spectral densities $\delta I_1$ and $\delta\sigma$:

$$W_2 = (\overline{\sigma})^2 \, W_1 + W_\bullet. \qquad\qquad (1.23)$$

Fig. 1.6.  Typical distribution of secondary electrons, dislodged/chased from metals, on energies:  $eV_2$ - energy of secondary electrons; $n(V_2)$ - number of secondary electrons of those possessing energy $eV_2$.

Page 24.

Usually is called secondary-electron only noise, connected to fluctuations of secondary-emission coefficient, i.e., components whose spectral density is reflected by second member of formula (1.23).  The spectral density of secondary-electron noise is designed from following formula [8]:

$$W_o = 2e(H - \bar{\sigma})\bar{\sigma}\,\bar{I}_1 = 2e(H - \bar{\sigma})\bar{I}_2, \qquad (1.24)$$

where H - coefficient, which depends just as $\vec{\sigma}$, from the energy of primary electrons and that exceeding value $\vec{\sigma}$ for several ones with the energy of primary electrons, calculated by hundred volts.

Let us note that low-velocity electrons in interelectrode space of klystron can appear not only due to secondary emission, but also as a result of ionization of molecules of residual gas.  The effect of

such electrons must be similar to the effect of slow secondary electrons; however, it seems to us that with the normal vacuum a quantity of them is small.

Flicker noise of cathode current. From the experiments it is known that the spectral noise density of cathode current substantially grows/rises with decrease in frequency F. This it is not possible to explain by the action of sources examined above of the noises of cathode current (shot, ionic), whose spectral density at the low frequencies is in effect constant.

Component of noise of cathode current, which calls increase in its spectral density at low frequencies, was called flicker noise. In the majority of the cases the spectral density of the flicker noise of the current of the oxide cathode, which works in the mode/conditions of space charge, is satisfactorily described by empirical formula [8]:

$$ W_{\phi} = \frac{a_1 I_{\kappa}'}{F^{\mu}} + \frac{a_2 I_{\kappa}'}{1 + (2\pi F \tau_0)^2} , \qquad (1.25) $$

where $\mu$ - is most frequently close to 1, $\nu$ - to 2. Values $a_1$ $a_2$ and $\tau_0$ depend on material, geometric dimensions and conditions for the work of cathode.

The physical nature of flicker noise of oxide cathode is complicated; picture almost always observed during experiment is result of joint action of several physical processes. All these

processes are characterized by inertness.

Page 25.

The electronic surges, caused by them, very slowly attenuate, as a result of which the spectral density of the fluctuations of current (result of the imposition of such surges) has strongly expressed low-frequency component. A number of processes, which call flicker effect, includes:

- fluctuations of the local work function of electrons from the cathode. They occur due to contact of extraneous atoms or ions with the surface of cathode, and also as a result of the heterogeneity of the diffusion of barium atoms from the inner layers of oxide coating for its surface. Sections forming in this case on the surface of cathode with the increased or lowered/reduced emission have the specific "lifetime"; a change in their state occurs slowly due to the inertness of those calling this phenomenon of physicochemical and diffusion processes;

- fluctuation of the resistor/resistance of the high-impedance layer between the oxide layer and the metallic support/base of cathode. This layer has semiconductive properties. The voltage/stress, which falls on the layer with the course through it of direct current, fluctuates due to a random change in the concentration of movable charge carriers. Latter/last process is inertial, since it is connected with the slow migration of admixed atoms in the layer. It is understandable that those arisen must cause the fluctuations of

the current through the instrument by such shape of the fluctuation of voltage/stress, since they operate consecutively/serially with direct/constant voltage, applied from without between the outputs of the cathode and anode;

- fluctuations of space charge near the cathode, which appear during capture in the region of the minimum of the potential of positive ines, emitted by cathode.  The seized ions can for long oscillate in potential well, partially compensating negative space charge, i.e., decreasing the depth of pit.  This causes the flashes/bursts of electronic current of the corresponding duration. Experiment shows that the spectral density of the fluctuations of current, caused by this process, is constant at the low frequencies and drops according to the law of $F^{-2}$ on the high, i.e. he is described by the second member of formula (1.25).  Transient frequency lies/rests at region of tens - hundred hertz [13].

Named reasons for generation of flicker noise of cathode current are not the only possible.  The complexity of the physicochemical structure of oxide cathodes and the heterogeneity (porosity) of their surface make the investigation of nature of flicker noise by very difficult.  Up to now number of questions, in particular the degree of the suppression of flicker noise by space charge, remains not completely clear.  The general theory, which could quantitatively describe the complex of the phenomena, which call flicker noise, was not created.  Only separate possible mechanisms are examined. Experimental data not always comparable due to the incompleteness of

the information about the physicochemical and structural state of cathode and vacuum. An important question about the spectrum of flicker noise at the lowest possible frequencies is not resolved. The survey/coverage of the works, dedicated to the investigation of flicker effect, can be found in monograph [11].

Page 26.

Interesting experimental data, which made it possible to explain the role of the separate sources of flicker noise, are obtained recently into [13]. At frequencies the spectral density of flicker noise, as a rule is below $10^3$-$10^4$ Hz, it exceeds the spectral density of complete shot noise and considerably exceeds the spectral density of the shot noise, suppressed by space charge. This makes flicker noise with one of the most dangerous sources of instability.

Surplus flicker noise in multielectrode tubes. The investigation of the fluctuations of current in the instruments with several positive electrodes shows that the level of flicker noise in the circuits of separate electrodes frequently exceeds the value, which it would be possible to expect, on the basis of the level of the flicker noise of the current of cathode. In a number of cases the correlation between the noise of the current of cathode and the noise in the circuit of any positive electrode is small. This speaks, that in the multielectrode instruments there are sources of surplus flicker noise, which operate independent of the flicker noise of cathode current. Surplus flicker noise was discovered in experiments with the tetrodes,

the pentodes and the tubes with secondary emission [14, 15, 103].

Authors [14, 15] consider that effects of current distribution in secondary emission are reason for surplus flicker noise.  It was above indicated that the same effects cause surplus noises with the uniform spectrum.  However, if physical nature of noises current distribution and secondary- electron noises with the uniform spectrum are completely clear and their theory is developed, this cannot be said about surplus flicker noise.  Nevertheless it cannot be ignored in the examination of the fluctuation properties of klystrons.  The information about level and spectrum of surplus flicker noise can be obtained from the experiment, studying the fluctuations of circuital current of the isolated/insulated grids of klystron.  Since in the majority of contemporary klystrons the grids are not isolated/insulated, for conducting such measurements the specially prepared mock-ups are necessary.

Noises of thermal origin.  The effective resistance, entering the circuits, connected with the electronic flux (for example, the effective resistance of resonator), are the source of thermal noises. The chaotic voltage/stress, which develops on these resistors/resistances, can modulate the velocity of electrons and increase thus the noisiness of ray/beam.  the spectral density of the mean square of thermal noise voltage, which develops on resistor/resistance of r, is given by Nyquist's formula:

$$W_r = 4kT_r r. \tag{1.26}$$

Here k - Boltzmann constant; $T_r$ - absolute temperature of the noisy

resistor/resistance.

Page 27.

Effects, called thermal noise, as a rule are considerably weaker than noise effect of electronic flux and therefore in examination of fluctuations in existing klystron oscillators with them need not be considered.

2.2.  Propagation of shf/SVCh noises in the electronic flux.

At superhigh frequencies time of electron motion in instrument considerably exceeds oscillatory period.  Under such conditions propagation along the electronic flux of any disturbance/perturbation, be it signal or noise, acquires specific features.

It is known that disturbances/perturbations are propagated along electronic flux in the form of waves of space charge [16].  During the propagation the continuous and mutual conversion of variable speed of electrons and kinetic energy connected with it into the variable/alternating density of space charge and the potential electric field energy connected with it occurs.  Similar to transmission modes in the waveguides, the waves of space charge are characterized by different forms of the distribution of the variable physical parameters over the cross section and by different phase speeds.  The difference between the waves of the waveguide and the waves of space charge consists, in particular, in the fact that in the first case we deal concerning the electromagnetic vibrations, which

are propagated rapidly (phase speeds of waveguide waves of more than

the speed of light), and secondly - with predominantly

electromechanical type oscillations/vibrations, which are propagated

it is comparatively slow (phase wave velocity of space charge they are

close to the average speed of electrons).

Simplest picture is formed in drifting one-dimensional electronic

flux, whose parameters do not depend on transverse coordinates.  In

this case all variables, which characterize the dynamic state of flow

(variable speed current density, the density of space charge, the

intensity/strength of longitudinal electric field), are propagated in

the form of two waves of space charge from somewhat distinguished

phase speeds.  The interference of these waves leads to the fact that

the amplitude of total oscillation periodically changes along the

ray/beam, similarly how this occurs in the presence of the

interference of straight line and reflected of waves in the waveguide.

Page 28.

Difference consists in the fact that in the first case a phase

difference of the interfering waves, which move to one side, is

changed from one point to the next due to the fact that their phase

speeds are different, and secondly - as a result of the counter motion

of the waves, which have identical with respect to value phase speed.

In contrast to one- dimensional case, in electronic flux of final

section is propagated not by one, but infinite number of pairs of

waves of space charge (each of them it consists of rapid and slow waves). If the distribution of initial disturbance in area of beam is close to the uniform, then wave amplitude of lowest (fundamental) type considerably exceeds the wave amplitudes of space charge of the highest types [1].

FOOTNOTE [1]. Lowest type of rapid and slow waves are characterized by the almost uniform distribution of disturbances/perturbations over area of beam; in highest type waves the periodicity of disturbances/perturbations along a radius and an azimuth occurs. ENDFOOTNOTE.

In the klystrons precisely this position occurs; therefore in the majority of the cases it is possible to examine only the propagation of the waves of fundamental type space charge, i.e., to reduce the problem to the one-dimensional, taking into account the finite quantity of area of beam by quantitative corrections [16].

One should note that wave theory of space charge is linear, i.e., it is suitable for describing propagation only of slight disturbances.

Wave theory of space charge is entirely applicable for describing noise propagation in electronic flux, since they cause slight disturbances. It is possible to obtain the simple correlations, which connect the spectral densities of the fluctuations of current and speed in two consecutive sections of electronic flux [11, 17]:

$$W_v(\omega, x) = A^2 W_v(\omega, 0) + B^2 W_i(\omega, 0) + 2AB \operatorname{Im} W_{iv}(\omega, 0),$$
$$W_i(\omega, x) = C^2 W_v(\omega, 0) + D^2 W_i(\omega, 0) + 2CD \operatorname{Im} W_{iv}(\omega, 0),$$
$$\operatorname{Im} W_{iv}(\omega, x) = AC W_v(\omega, 0) + BD W_i(\omega, 0) +$$
$$+ (AD + BC) \operatorname{Im} W_{iv}(\omega, 0),$$
$$\operatorname{Re} W_{iv}(\omega, x) = \operatorname{Re} W_{iv}(\omega, 0). \tag{1.27}$$

Here $W_i(\omega, x)$ and $W_v(\omega, x)$ - spectral densities of the mean squares of the fluctuations of current and speed; $W_{iv}(\omega, x)$ - mutual spectral density of these fluctuations, which is the measure for the correlation between them.

Obviously, $W_i(\omega, 0)$, $W_v(\omega, 0)$ and $W_{iv}(\omega, 0)$ should be considered as spectral densities of fluctuations, which excite waves of space charge in the beginning of section of electronic flux (with x=0).

Page 29.

Coefficients A, B, C, D, are determined by the average parameters of electronic flux, by the length of the section in question, and also by frequency $\omega$. During the conclusion/output of these expressions the model of one-dimensional one-velocity flow was accepted. They are valid not only for the drifting electronic flux, but also for the flow with a smooth change in the average velocity of electrons. In the particular case of the drift of expression (1.27) they take the form

$$W_v(\omega, x) = \cos^2 \frac{\omega_p x}{v_0} W_v(\omega, 0) + \left(\frac{\omega_p}{\omega} \frac{v_0}{I_0}\right)^2 \sin^2 \frac{\omega_p x}{v_0} \times$$
$$W_i(\omega, 0) - \frac{\omega_p}{\omega} \frac{v_0}{I_0} \sin^2 \frac{\omega_p x}{v_0} W_{iv}(\omega, 0),$$
$$W_i(\omega, x) = \left(\frac{\omega}{\omega_p} \frac{I_0}{v_0}\right)^2 \sin^2 \frac{\omega_p x}{v_0} W_v(\omega, 0) +$$
$$+ \cos^2 \frac{\omega_p x}{v_0} W_i(\omega, 0) + \frac{\omega}{\omega_p} \frac{I_0}{v_0} \sin^2 \frac{\omega_p x}{v_0} W_{iv}(\omega, 0), \tag{1.28}$$

$$\operatorname{Im} W_{iv}(\omega, x) = \cos^2 \frac{\omega_p x}{v_0} \operatorname{Im} W_{iv}(\omega, 0) +$$
$$+ \frac{1}{2} \left[ \frac{\omega}{\omega_p} \frac{I_0}{v_0} W_v(\omega, 0) - \frac{\omega_p v_0}{\omega I_\bullet} W_i(\omega, 0) \right] \sin^2 \frac{\omega_p x}{v_0},$$
$$\operatorname{Re} W_{iv}(\omega, x) = \operatorname{Re} W_{iv}(\omega, 0),$$

where $I_\bullet$, i $v_\bullet$ - average/mean current and velocity of electrons; $\omega_p$ - natural vibration frequency of the electronic plasma of ray/beam, determined by the average density of space charge $\rho_0$:

$$\omega_p = \sqrt{\frac{e}{m} \frac{\rho_0}{\epsilon_0}}. \qquad (1.29)$$

The finite dimensions of area of beam can be taken into consideration in (1.28) by the replacement of the frequency of plasma $\omega_p$ for the reduced frequency of plasma $\omega_q = R^2 \omega_p$, where $R^2 < 1$ - coefficient of reduction, depending on the frequency of disturbances/perturbations, average speeds of electrons, diameters of the drift tube and ray/beam [16].


Initial spectral densities of fluctuations $W_v(\omega, 0)$,
$W_i(\omega, 0)$, $W_{iv}(\omega, 0)$ can be assigned in the beginning of region of drift, i.e., at output of electron gun.  In order to determine the connection/communication of these values with spectral densities of noises in the field of the minimum of potential, it is possible, it would seem, to use relationships/ratios (1.27), having correspondingly determined coefficients of A, B, C, D.  Unfortunately this is not the case.

Page 30.

Matter in the fact that formulas (1.27) are obtained for the
one-velocity model of electronic flux and cannot be used them in the
region of the minimum of the potential, where the scatter of
velocities of electrons let us compare it with their average speed.
The analysis of noise propagation in this region is very complex; the
results, obtained in [18, 19] and confirmed by experiment with the
construction of the low-noise travelling-wave tubes, they show that
the important processes, which lead to the establishment of the
correlation between the noises of current and speed, here occur.  The
data, obtained in the works indicated, make it possible to assign
initial spectral noise densities at a sufficient removal/distance from
the region of the minimum of the potential, where the electron stream
it is possible to consider it one-velocity which makes it possible to
utilize for further translation of the noises of relationship/ratio
(1.27).

Thus, problem of translation of noises in any section of
electronic flux in principle is solved.  The possibility of
calculating the distribution of the spectral density of noise current
along the electron beam has important value for engineering the
low-noise shf instruments, since it makes it possible to find the
coordinate, in which noise current is minimal.  Arranging/locating at
this point resonator, it is possible to decrease the noise in its gap.
Computations and experiment show that in the case thin, of the rigidly
focused with magnetic field electronic fluxes, whose properties are

close to the one-dimensional, the difference in the levels of noise

current in maximums and minimums of standing wave reaches 15-20 dB,

which indicates the significant magnitude of gain.  However, such

electronic fluxes are utilized only in low-power LBV.  The electronic

fluxes of generator klystrons essentially from them differ.  Usually

they are focused electrostatically, their diameter is comparatively

great, and electron optics of gun is sufficiently rough, especially in

the low-voltage klystrons.  Under the conditions indicated in the

electron gun appear the surplus of shf noises, which significantly

raise the level of the fluctuations of current in the minimum of erect

noise wave.


Let us point out fundamental reasons for their appearance.


1.  Heterogeneity of emission over surface of cathode.  The

heterogeneity of emission is connected both with grain structure of

the emitting surface and with the temperature differentials.  It is

possible to show that both these reasons lead to an increase in the

amplitudes of the noise waves of space charge of highest types [11,

20, 21].  At first glance this does not present danger, since the

field of high-frequency gaps is relatively uniform and therefore it

interacts in essence with the waves of fundamental type space charge.

Page 31.

However, due to nonlamellar nature of electronic flux and current

interception occurs the redistribution of the wave amplitudes of space

charge, as a result of which the noise energy, transferred by the waves of space charge of the highest types, is transmitted to fundamental type wave. Available experimental data confirm this mechanism [22].

2. Lens effects. In the electron guns, which form convergent beam, the field of orificed anode operates as electrostatic lens. The combined action of this field and space charge of ray/beam changes electron path, converting the convergent flow into the cylindrical. As calculations and experiment [11, 23] are shown, in this case increase the fluctuations of longitudinal velocity of electronic flux. The greater the initial angle of convergence of ray/beam, the more considerable the increment in the fluctuations.

3. Current interception. As a result of current interception the noises of current distribution appear. The mechanism of their appearance on shf in fundamental the same and at the low frequencies; let us note that current interception they accompany the transformation of the transmission modes of space charge.

4. Modulation of space charge near the cathode by electrons, which return to cathode (in reflex klystrons).

Theory of surplus shf noises is at present developed insufficiently; therefore reliable information about complete noise level and its change along electronic flux can be obtained only from

experiment.

Scarce experimental data indicate that in low-vol'age klystrons
of short-wave part of range of microwaves effect of surplus noises is
great; complete level of shf noise current of ray/beam in order
approaches complete shot and, apparently, little is changed with
coordinate.  In the high-voltage klystrons it is possible to expect
the smaller noisiness of ray/beam, especially in the long-wave section
of the range of microwaves.  In this case the selection of the
rational position of resonator can lead to the decrease of the effect
of shf noises; however, the freedom of this selection is limited by
the small length of the electro-statistically focused flow.

3.  Effect of the noises of electronic flux on amplitude and frequency
of klystron oscillator.

Let us examine how noises of electronic flux affect frequency and
amplitude of oscillations of reflex klystron.  For clarity and
simplicity we utilize during the solution of this problem a
quasi-static method, on the basis of the equation of steady-state
oscillations.

Page 32.

Equivalent diagram of reflex klystron is represented in Fig.
1.7.  The complete conductance of gap, which includes the conductivity
of losses in resonator $g_p$, the conductivity of external load $g_н$,

converted to the gap through the coupling element, and the active part of the electronic conductivity of gap $g_{e'}$ is equal to $g = g_\text{p} + g_\text{н} + G_e.$ Complete susceptance of gap, which consists of susceptance of resonator $\omega C - (1/\omega L)$ and reactive part of the electronic conductivity of gap $b_{r'}$ is equal to $b = \omega C - (1/\omega L) + b_e.$ The electronic conductivity of gap $g_e + jb_e$ should not be confused with the electronic conductivity of klystron $G_e + jB_e$ [see equation (1.5). The first is determined by grouping in the gap, and the second - in the decelerating field.

If instantaneous voltage on gap is assigned in the form of $u(t) = U \sin \omega t$, then

$$\left.\begin{aligned}
\dot{U} &= -jU, \\
\dot{I}_\text{н} &= 2MIJ_1\left(\frac{MU\theta}{2V_0}\right)e^{-j\theta} = I_\text{н}e^{-j\theta},
\end{aligned}\right\} \quad (1.30)$$

where $\dot{I}_\text{н}$ - complex amplitude of fundamental harmonic of induced current; $\dot{U}$ - complex amplitude of voltage/stress on gap. Current I is connected with the current of cathode with the relationship/ratio

$$I = \beta I_\text{к}, \qquad (1.31)$$

where $\beta$ - coefficient, which considers all losses of current on the way from cathode into the decelerating field and back to gap. If in the klystron are three grids (grid of anode of projector and two grids, the generatrices gap), then $\beta = \beta_1\beta_2\beta_3{}^2$, where $\beta_1$, $\beta_2$, $\beta_3$ - coefficients of transmission of the grids indicated.

Equation describing diagram in Fig. 1.7 for first (fundamental) harmonic of oscillations, is expressed as follows:

$$\dot{I}_\text{н} + \dot{U}(g + jb) = 0.$$
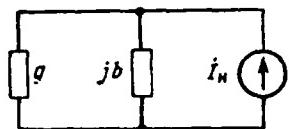
Fig. 1.7. Equivalent diagram of reflex klystron.

Page 33.

Taking into account nearness of oscillation frequency to resonance frequency of oscillatory circuit, it is possible to utilize approximation for complete susceptance b:

$$b = \omega C - (1/\omega L) + b_e \approx 2C(\omega - \omega_{\kappa}) + b_e = 2C(\omega - \omega_0), \quad (1.32)$$

where $\omega_{\kappa} = 1/\sqrt{LC}$ - natural frequency of "cold" resonator; $\omega_0 = \omega_{\kappa} - (b_e/2C)$ - natural frequency of resonator, loaded with electronic flux, that differs from $\omega_{\kappa}$ due to effect of reactive component electronic load of gap.

Aforesaid makes it possible to rewrite equation of oscillations as follows:

$$I_{\text{н}} = -\dot{U}[g + j2C(\omega - \omega_0)]. \quad (1.33)$$

After substituting here $\dot{U}$ and $I_{\text{н}}$ from (1.30) and after isolating the imaginary and real parts, let us find:

$$gU = -2MI\,J_1\left(\frac{MU\theta}{2V_0}\right)\sin\theta,$$
$$2C(\omega - \omega_0)U = -2MIJ_1\left(\frac{MU\theta}{2V_0}\right)\cos\theta. \quad \left.\right\}\quad (1.34)$$

These equations describe steady-state oscillations from reflector klystron, determining their amplitude and frequency.

3.1.  Fluctuations of modulation (low-frequency) origin.

Noise effect in electronic flux leads to the fact that amplitude and oscillator frequency continuously fluctuate; in this case their average/mean values remain constants.

By simplest and obvious reason for fluctuations is modulation of oscillation low-frequency components of noises.  Since the noise level is very small, the modulating noise spectra are converted into the spectra of fluctuations linearly, i.e., spectral component of fluctuations at the certain frequency F is caused by spectral components of the noises of the ray/beam only of the same frequency. Therefore during the analysis of the fluctuations of modulation origin it is possible to take only that region of the spectrum of noises, which coincides with the region of the spectrum of fluctuations in question into consideration.  In the majority of the cases they are interested in the Doppler frequency band of the fluctuations, which stretches from ten or hundred hertz to hundreds of kilohertz (see Chapter 3).  This means that the fluctuation of oscillation and their calling noises can be considered the processes, slow in comparison with "carrying" oscillation itself and even with the transient processes, whose rate is determined by the time constant (by passband) of resonator.

Page 34.

Actually, the high-frequency boundary of the frequency band of the fluctuations indicated lies/rests at area of hundreds of kilohertz, the carrier frequency is measured by thousands of megahertz, and the passband of resonator - usually ten megahertz.

Slowness of processes in question makes it possible to utilize for calculating fluctuations of equation of steady state (1.34). In the description of steady-state oscillations the coefficients in these equations are constant: the action of low-frequency noises produces slow and small in the value changes in these coefficients, which, in turn, leads to the fluctuations of amplitude and frequency. With the aid of equations (1.34) it is possible·to find the connection/communication between the instantaneous values of fluctuations and their calling noises. This method of calculation assumes that the transient processes are absent, i.e., amplitude and frequency are the inertia-free functions of the randomly changing parameters of klystron.

Let us rewrite equations (1.34), after substituting in them $\omega_0$ from (1.32) and after taking into consideration, that $g = g_p + g_{\scriptscriptstyle \parallel} + g_e$:

$$
\left.
\begin{aligned}
(g_p + g_{\scriptscriptstyle \parallel} + g_e)\, U &= 2MIJ_1 \left( \frac{MU\theta}{2V_0} \right) \cos \Delta\theta, \\
2C \left( \omega - \omega_{\scriptscriptstyle \kappa} + \frac{b_e}{2C} \right) U &= -2MIJ_1 \left( \frac{MU\theta}{2V_0} \right) \sin \Delta\theta.
\end{aligned}
\right\} \quad (1.35)
$$

Here $\Delta\theta = \theta - 2\pi(N + 3/4)$ - divergence of the transit angle of electrons in

the decelerating field from its optimum value, equal to $2\pi(N+3/4)$.
During the noise effect fluctuate the following parameters in the
equations:

1.  Current of ray/beam $I = \bar{I} + \delta I(t)$.

2.  Electronic conductivities $g_e = \bar{g}_e + \delta g_e(t), b_e = \bar{b}_e + \delta b_e(t)$.   The
electronic load of gap is created by both the fast beam electrons and
by slow secondary electrons, dislodged/chased from the grids.  The
fluctuations of primary electronic and secondary-electron currents
cause the fluctuations of electronic conductivities.

3.  Transit angle of electrons in decelerating field $\theta = \vec{\theta} + \delta\theta(t)$
[respectively $\Delta\theta = \overline{\Delta\theta} + \delta\theta(t)$].  These fluctuations appear as a result of
the effect of the fluctuations of the initial velocity of electrons
and fluctuations of the density of the space charge of ray/beam for
the electron transit time in the decelerating field.  In turn the
fluctuations of space charge are caused by fluctuations in the current
of ray/beam.

Page 35.

After representing unknown solutions for amplitude and
frequencies in the form of sums of average/mean values and
fluctuations $U = \bar{U} + \delta U(t)$, $\omega = \bar{\omega} + \delta\omega(t)$, we can rewrite equations (1.35)
taking into account disturbances/perturbations of their coefficients
as follows:

$$
\left.
\begin{aligned}
& [g_p + g_{\scriptscriptstyle K} + \bar{g}_e + \delta g_e(t)][\bar{U} + \delta U(t)] = 2M[\bar{I} + \\
& + \delta I(t)] J_1\left\{\frac{M[\bar{U} + \delta U(t)]\bar{\theta}}{2V_0}\right\} \cos[\overline{\Delta\theta} + \delta\theta(t)], \\
& 2C\left[\bar{\omega} + \delta\omega(t) - \omega_{\scriptscriptstyle K} + \frac{\bar{b}_e}{2C} + \frac{\delta b_e(t)}{2C}\right][\bar{U} + \delta U(t)] = \\
& = -2M[\bar{I} + \delta I(t)] J_1\left\{\frac{M[\bar{U} + \delta U(t)]\bar{\theta}}{2V_0}\right\} \sin[\overline{\Delta\theta} + \\
& + \delta\theta(t)].
\end{aligned}
\right\}
\quad (1.36)
$$

During conclusion/output (1.36) we disregarded/neglected straight/direct effect of fluctuations of rate and transit angle on amplitude of induced current, after substituting into argument of Bessel function average/mean values of transit angle $\bar{\theta}$ and potential of electrons $V_e$. It is possible to show that error connected with this simplification affects the accuracy of the calculation of the fluctuations of amplitude in essence. In the most interesting mode/conditions (optimum grouping, nearness to the center of the zone of generation) the error is negligible.

Low value of fluctuations in comparison with average/mean values makes it possible to linearize equations (1.36) for all fluctuation terms, after which equation they take the form:

$$(g_p + g_n + \bar{g}_e)\overline{U} + (g_p + g_n + \bar{g}_e)\delta U(t) + \overline{U}\delta g_e(t) =$$
$$= 2M\bar{I}J_1\left(\frac{M\overline{U}\bar{\theta}}{2V_0}\right)\cos\overline{\Delta\theta} + 2MJ_1\left(\frac{M\overline{U}\bar{\theta}}{2V_0}\right)\cos\overline{\Delta\theta}\,\delta I(t) +$$
$$+ M\bar{I}J_1'\left(\frac{M\overline{U}\bar{\theta}}{2V_0}\right)\cdot\frac{M\bar{\theta}}{2V_0}\cos\overline{\Delta\theta}\delta U(t) -$$
$$- 2M\bar{I}J_1\left(\frac{M\overline{U}\bar{\theta}}{2V_0}\right)\sin\overline{\Delta\theta}\delta\theta(t),$$
$$2C\left(\bar{\omega} - \omega_x + \frac{b_e}{2C}\right)\overline{U} + 2C\left(\bar{\omega} - \omega_x + \frac{b_e}{2C}\right)\delta U(t) +$$
$$+ 2C\overline{U}\delta\,\omega(t) + \overline{U}\delta b_e(t) = -2M\bar{I}J_1\left(\frac{M\overline{U}\bar{\theta}}{2V_0}\right)\sin\overline{\Delta\theta} -$$

$$(1.37)$$

$$-2MJ_1\left(\frac{M\overline{U}\,\overline{\theta}}{2V_0}\right)\sin\overline{\Delta\theta}\delta I(t)-2M\,\overline{I}J_1'\left(\frac{M\,\overline{U}\,\overline{\theta}}{2V_0}\right)\times$$
$$\times\frac{M\overline{\theta}}{2V_0}\sin\overline{\Delta\theta}\,\delta U(t)-2M\overline{I}J_1\left(\frac{M\overline{U}\,\overline{\theta}}{2V_0}\right)\cos\overline{\Delta\theta}\delta\theta(t).$$

For average/mean values equations of steady state (1.35) must be fulfilled

$$\left.\begin{aligned}(g_p+g_{\text{н}}+g_e)\,\overline{U}&=2M\,\overline{I}\,J_1\left(\frac{M\overline{U}\overline{\theta}}{2V_0}\right)\cos\overline{\Delta\theta},\\ 2C\left(\overline{\omega}-\omega_{\text{к}}+\frac{\overline{b}_e}{2C}\right)\overline{U}&=-2M\overline{I}J_1\left(\frac{M\overline{U}\overline{\theta}}{2V_0}\right)\sin\overline{\Delta\theta}\,.\end{aligned}\right\}\quad(1.38)$$

Deducting these equations from appropriate equations of system (1.37), we obtain equations for fluctuations

$$\left[g_p+g_{\text{н}}+\overline{g}_e-2M\,\overline{I}\,J_1'\left(\frac{M\overline{U}\,\overline{\theta}}{2V_0}\right)\frac{M\overline{\theta}}{2V_0}\,\cos\overline{\Delta\theta}\right]\delta U(t)=$$
$$=-\overline{U}\delta g_e(t)+2MJ_1\left(\frac{M\overline{U}\overline{\theta}}{2V_0}\right)\cos\overline{\Delta\theta}\delta I(t)-2M\,\overline{I}J_1\left(\frac{M\overline{U}\,\overline{\theta}}{2V_0}\right)\times$$
$$\times\sin\overline{\Delta\theta}\delta\theta(t),$$
$$2C\overline{U}\delta\omega(t)=-\left[2C\left(\overline{\omega}-\omega_{\text{к}}+\frac{b_e}{2C}\right)+2M\overline{I}J_1'\left(\frac{M\overline{U}\overline{\theta}}{2V_0}\right)\times\right.$$
$$\left.\times\frac{M\overline{\theta}}{2V_0}\sin\overline{\Delta\theta}\,\right]\delta U(t)-\overline{U}\delta b_e(t)-2MJ_1\left(\frac{M\overline{U}\overline{\theta}}{2V_0}\right)\sin\overline{\Delta\theta}\delta I(t)-$$
$$-2M\,\overline{I}J_1\left(\frac{M\overline{U}\overline{\theta}}{2V_0}\right)\cos\overline{\Delta\theta}\delta\theta(t).$$

After conversions, for which is used connection/communication between average parameters, caused by equations (1.38), and recursion formulas for functions of Bessel

$$J_1(x)=\frac{x}{2}[J_0(x)+J_2(x)],\quad J_1'(x)=\frac{1}{2}[J_0(x)-J_2(x)],$$

fluctuation of frequency and relative fluctuations of amplitude

$\delta U(t)/\bar{U}$ are expressed by simple formulas:

$$\frac{\delta U(t)}{\bar{U}} = \frac{J_1(\overline{X})}{\overline{X} J_2(\overline{X})} \left[ \frac{\delta I(t)}{\bar{I}} - \frac{\delta g_e(t)}{\bar{g}} - \delta\theta(t) \, \mathrm{tg} \, \overline{\Delta\theta} \right],$$

$$\delta\omega(t) = \frac{\bar{\omega}}{2Q_{\mathrm{H}}} \left[ - \frac{\delta b_e(t)}{\bar{g}} - \frac{\delta g_e(t)}{\bar{g}} \, \mathrm{tg} \, \overline{\Delta\theta} - \frac{\delta\theta(t)}{\cos^2 \overline{\Delta\theta}} \right], \quad (1.39)$$

where $\bar{g} = g_\mathrm{p} + g_\mathrm{H} + \bar{g}_e$ - complete average/mean conductance of gap:
$Q_\mathrm{H} = \omega C/\bar{g}$ - quality of loaded resonator; $\overline{X} = MU\theta/2V_0$ - average bunching
parameter.

Page 37.

In center zones of oscillations ($\overline{\Delta\theta} = \theta$) of fluctuation of
amplitude are defined only by fluctuations of current $\delta I(t)$ and by
fluctuations of active electronic conductivity, and fluctuations of
frequency - by fluctuations of reactive/jet electronic conductivity
and by fluctuations of transit angle $\delta\theta(t)$. The straight/direct
effect of the fluctuation of current on $\delta\omega(t)$ is absent.

$\delta I(t), \; \delta g_e(t), \; \delta b_e(t), \; \delta\theta(t)$        with initial noises of electronic flux now
remains to connect.

Fluctuations in electron stream $\delta I(t)$ reflected. In accordance
with (1.31) $I = \beta I_\kappa$. The fluctuations of current I are caused not only
by the noise of cathode current, but also appearing with the
interception of electrons by grids by the noise of the current
distribution:

$$\delta I(t) = \beta \delta I_{\kappa}(t) + \delta I_{\tau}(t), \quad \text{where} \quad \delta I_{\tau}(t)$$

- fluctuations of current distribution.  In turn,

$$\delta I_{\kappa}(t) = \delta I_{\text{др}}(t) + \delta I_{j}(t) + \delta I_{\phi}(t) \ ^{1}, \quad \text{where} \quad \delta I_{\text{др}}(t) \quad \text{and} \quad \delta I_{j}(t)$$

- low-frequency components of shot and ionic noises, and $\delta I_{\phi}(t)$ –
flicker noise of cathode current.

FOOTNOTE [1].  In $\delta I_{\kappa}(t)$ for simplicity the effect of the electrons, which return to the cathode from the region of reflector, is not taken into consideration.  Experiment shows that such electrons, acting on the minimum of potential near the cathode, increase the noise level of cathode current.  This occurs due to the fact that the electronic flux, which returns to the cathode, is modulated by the noises of current distribution and by amplitude noise.  The phenomenon indicated is not reflected in the evaluations/estimates, given further, since the straight/direct effect of the noises of current distribution on the oscillation prevails.  ENDFOOTNOTE.

Thus,

$$\delta I(t) = \beta [\delta I_{\text{др}}(t) + \delta I_{j}(t) + \delta I_{\phi}(t)] + \delta I_{\tau}(t). \qquad (1.40)$$

Fluctuations of electronic conductivities $\delta g_{e}(t)$ and $\delta b_{e}(t)$. Electronic conductivities appear both with the straight line and with the reverse transit of the electrons through the gap and have components, by specified load gap by the flow of the primary (fast) and secondary (slow) electrons, dislodged/chased from the grids of the

klystron:

$$g_e = g'_{e1} + g^{\downarrow}_{e1} + g'_{e2} + g^{\downarrow}_{e2},$$
$$b_e = b'_{e1} + b^{\downarrow}_{e1} + b'_{e2} + b^{\downarrow}_{e2}. \qquad (1.41)$$

Page 38.

Here index "1" designates primary-electronic, index "2" -
secondary-electron conductivities. Mark in the form of arrow/pointer
by point upward indicates that the conductivities are connected with
the straight/direct flight/span of electrons, by point down - with the
reverse/inverse.

    primary-electronic conductivities are determined by known
formulas [1]:

$$g^{\uparrow}_{e1} = \frac{I^{\uparrow}}{2V_0\theta^2_g} [2(1 - \cos\theta_g) - \theta_g \sin\theta_g],$$
$$b^{\uparrow}_{e1} = \frac{I^{\uparrow}}{2V_0\theta^2_g} [2\sin\theta_g - \theta_g(1 + \cos\theta_g)]. \qquad (1.42)$$

    For secondary-electron conductivities we utilize following
expressions:

$$g^{\uparrow}_{e2} = \frac{I^{\uparrow}_2}{V_0\theta^2_g}, \quad b^{\uparrow}_{e2} = -\frac{I'_2 \cdot \bar{\theta}_{g2}}{2V_0\theta^2_g}. \qquad (1.43)$$

    In (1.42) and (1.43) are used these designations:  $\theta_g$ - transit
angle of primary (fast) electrons in gap, $I'_1$ and $I_1$ - currents of
primary electrons, which intersect gap with straight/direct and
reverse transits flights/spans respectively, $I'_2$ and $I_2$ - currents of

secondary electrons, dislodged/chased from grids with straight/direct and reverse transits through gap (Fig. 1.8), $\bar{\theta}_{g2}$ - mean angle of flight/span of secondary (slow) electrons in gap. Value $\bar{\theta}_{g2}$ is located by the averaging of the time of flight of secondary electrons over their initial velocities.
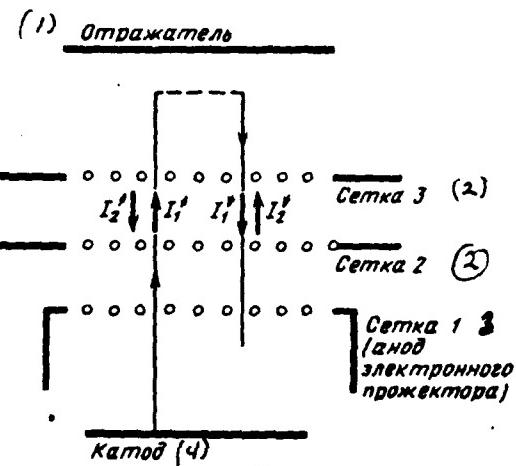
Fig. 1.8.  Diagram, which elucidates notation of currents of primary and secondary electrons accepted between grids of resonator gap. Key:  (1).  Reflector.  (2).  Grid.  (3).  Grid 1 (anode of electron gun).  (4).  Cathode.

Page 39.

For the contaminated metallic surfaces the maximum of the function of the distribution of secondary electrons through the rates is located approximately 3 eV over a wide range of a change in the energy of the primary electrons, which bombard surface.  Hence follows that approximate value $\bar{\theta}_{g2}$ can be found from formula $\bar{\theta}_{g2} \approx \theta_g \sqrt{\dfrac{V_0}{3}}$ ($V_0$ - in volts). In particular with $V_0 = 300$ $V$ the mean angle of flight/span $\bar{\theta}_{g2} \approx 10\theta_g$ and $b'_{e2} \approx -\dfrac{5}{\theta_g} \dfrac{I'_{02}}{V_0}$.

In [12] are given more exact expressions for secondary-electron conductivities, which appear with reverse transits of electrons through gap $g'_{e2}$ and $b'_{e2}$. In contrast to $g'_{e2}$ and $b'_{e2}$, which are created

by the electron stream $g_{c2}$ unmodulated on the density and $b_{c2}$ appear during the bombardment of grid with electron stream grouped in the field of reflector, and their value depends on bunching parameter and transit angle of primary electrons in the decelerating field. In (1.43) this dependence is not considered. Neglect of dependence $b_{c2}$ on X and $\theta$ does not lead to the inadmissible errors, since the effect of the parameters indicated on $b_{c2}$ is very weak [12]. As far as value $g_{c2}$ is concerned with the typical values $\theta_g$, $\theta$ and X it can prove to be considerably less than calculated by formula (1.43). However, the complete value of secondary-electron conductance, equal to sum $g_c'$ and $g_c''$, it decreases not more than twice, even if $g_c'$ becomes zero.

Thus, designing $g_c'$ from formula (1.43), we overstate its value. It will be shown below that in spite of this the effect of active secondary-electron conductivities during the fluctuation it is weak, which justifies the made assumption.

Page 40.

Thus

$$
\begin{aligned}
\delta g_e(t) &= \bar{g}'_{e1}\frac{\delta I'(t)}{\overline{I'}} + \bar{g}''_{e1}\frac{\delta I'(t)}{\overline{I'}} + \\
&+ \bar{g}'_{e2}\frac{\delta I'_2(t)}{\overline{I'_2}} + \bar{g}''_{e2}\frac{\delta I''_2(t)}{\overline{I''_2}}, \\
\delta b_e(t) &= \bar{b}'_{e1}\frac{\delta I'(t)}{\overline{I'}} + \bar{b}''_{e1}\frac{\delta I'(t)}{\overline{I'}} + \\
&+ \bar{b}'_{e2}\frac{\delta I'_2(t)}{\overline{I'_2}} + \bar{b}''_{e2}\frac{\delta I''_2(t)}{\overline{I''_2}}.
\end{aligned} \right\}
\qquad (1.44)
$$

Regarding $I^{\cdot}$ is current, which intersects gap with reverse transits i.e., $I^{\cdot}=I$. In accordance with (1.31) and (1.40)

$$\delta I^{\cdot}(t) = \delta I(t) = \beta[\delta I_{ap}(t) + \delta I_j(t) + \delta I_{\phi}(t)] + \delta I_\tau(t).$$

Current $I^{\cdot}$ with the straight/direct flight/span of gap somewhat more than current $I^{\cdot}$ (to the strength of current, intercepted by the grid, nearest to the reflector, with the straight/direct and reverse electron motion). This difference is small, since the coefficient of transmission of grid is close to one. Therefore for the simplification we will count $I^{\cdot} \approx I^{\cdot}$; we will also consider it identical of the fluctuation of these currents. Since into expressions for $\delta g_e(t)$ and $\delta b_e(t)$ enter ratios $\delta I^{\cdot}(t) \overline{I^{\cdot}}$ and $\delta I^{\cdot}(t) \overline{I^{\cdot}}$, the error, connected with the approximation/approach, will touch in the final analysis only of the fluctuations of the current distribution, which in actuality in currents $I^{\cdot}$ and $I^{\cdot}$ are not completely correlated.

Let us examine fluctuations of secondary-electron currents. If $\beta_\nu$ - coefficient of transmission $\nu$-thof the grid of gap, which approaches the current of primary electrons $I_\nu$, and $\sigma_\nu$ - secondary-emission coefficient, averaged over the surface of grid, then the current of secondary electrons is equal to $I_{2\nu} = \sigma_\nu(1-\beta_\nu)I_\nu$. In § 2 it was shown that the fluctuations of secondary-electron current were caused not only by the fluctuations of the current of primary electrons, but also by the fluctuations of secondary-emission coefficient, i.e.

$$\delta I_{2\nu}(t) = \overline{\sigma}_\nu(1-\beta_\nu)\delta I_\nu(t) + (1-\beta_\nu)\overline{I}_\nu \delta\sigma_\nu(t).$$

Average/mean secondary- electron current is equal to $\bar{I}_{2v} = \bar{\sigma}_v(1 - \beta_v)\bar{I}_v$. Let us designate part $\delta I_{2v}(t)$, caused by fluctuations $\sigma_v$ through $\delta i_{\sigma v}(t)$ (strictly secondary-electron noise). Then relation $\delta I_{2v}(t)/\bar{I}_{2v}$ can be recorded as follows:

$$\frac{\delta I_{2v}(t)}{\bar{I}_{2v}} = \frac{\delta I_v(t)}{\bar{I}_v} + \frac{\delta i_{\sigma v}(t)}{\bar{I}_{2v}} \,.$$

Taking into account the above expression (1.44) for fluctuations of electronic conductivities they take the form:

$$
\begin{aligned}
\delta g_e(t) &= \bar{g}_e \left[ \frac{\delta I_{ap}(t)}{\bar{I}_\kappa} + \frac{\delta I_J(t)}{\bar{I}_\kappa} + \frac{\delta I_\Phi(t)}{\bar{I}_\kappa} + \right. \\
&\quad \left. + \frac{\delta I_\tau(t)}{\beta \bar{I}_\kappa} \right] + \bar{g}'_{e2} \frac{\delta i'_2(t)}{\bar{I}'_2} + \bar{g}'_{e2} \frac{\delta i'_2(t)}{\bar{I}'_2} \,, \\
\delta b_e(t) &= \bar{b}_e \left[ \frac{\delta I_{ap}(t)}{\bar{I}_\kappa} + \frac{\delta I_J(t)}{\bar{I}_\kappa} + \frac{\delta I_\Phi(t)}{\bar{I}_\kappa} \frac{\delta I_\tau(t)}{\beta \bar{I}_\kappa} \right] + \\
&\quad + \bar{b}'_{e2} \frac{\delta i'_2(t)}{\bar{I}'_2} + \bar{b}'_{e2} \frac{\delta i'_\sigma(t)}{\bar{I}'_2} \,.
\end{aligned}
\qquad (1.45)
$$

here $\bar{g}_e = \bar{g}'_{e1} + \bar{g}'_{e1} + \bar{g}'_{e2} + \bar{g}'_{e2}$ and $\bar{b}_e = \bar{b}'_{e1} + \bar{b}'_{e1} + \bar{b}'_{e2} + \bar{b}'_{e2}$ - average/mean values of complete electronic conductivities.

Page 41.

Fluctuations of transit angle of electrons in decelerating field $\delta\theta(t)$. The fundamental sources of the fluctuations of the electron transit time in the field of reflector are the fluctuations of the initial velocity of electrons and density of space charge in the space between the reflector and the resonator, called fluctuations of the current of ray/beam. A precise analysis of the combined action of these sources is difficult. Since the problem examined/considered by us is solved approximately, we will be restricted in this case to

simple evaluations/estimates, without taking into account space-charge effect during the calculation of the action of the fluctuations of rate and considering that the fluctuations of space charge are caused only by the noises of the current of ray/beam. Let us present the fluctuation of transit angle by the sum: $\delta\theta(t)=\delta\theta_v(t)+\delta\theta_i(t)$, where $\delta\theta_v(t)$ and $\delta\theta_i(t)$ - components, caused by the fluctuations of rate and current respectively. During computation $\delta\theta_v(t)$ we will proceed from the kinematic expression for the transit angle of electrons in the decelerating field: $\theta=4\omega l_R V_0/v_0 V_z$, where $l_R$ - distance between the resonator and the reflector, and $V_z$ - potential difference between them. Since $V_0 = mv_0^2/2e$, then $\theta$ it is possible to rewrite thus: $\theta=4\omega l_R mv_0/2eV_z$, whence

$$\delta\theta_v(t) = \frac{4\omega l_R m}{2eV_z}\delta v_0(t) = \bar{\theta}\frac{\delta v_0(t)}{v_0}.$$

For computing component $\delta\theta_i(t)$ we utilize results of work [24], in accordance with which connection/communication between fluctuations of transit angle and fluctuations of current appears as follows:

$$\delta\theta_i(t) = -2\bar{\theta}F_J\frac{\delta I_R(t)}{\bar{I}_R}, \qquad (1.46)$$

where $\bar{I}_R$ and $\delta I_R(t)$ - average/mean and fluctuation currents, which enter decelerating field, $F_J = F_J(a_q, \tau_q)$ - function, which depends on average density of space charge of electrons in decelerating field; graph/curve of this function, borrowed of [24], is given in Fig. 1.9.

Page 42.

Along the axis of abscissas value

$$\tau_q = \frac{(\bar{\theta} - \theta)\lambda J_0^{1/2}}{2\pi \cdot 4{,}63 \, V_0^{1/4}} \, ,$$

where $\lambda$ - wavelength, cm, is plotted; $V_0$ - potential of resonator, $V$ ; $J_0$ - current density in the decelerating field $A/cm^2$.  During computation $J_0$ it is necessary bear in mind both the straight line, and from reflected electron streams.  As the parameter of the family of functions $F_J(a_q, \tau_q)$ serves relation $a_q = \frac{|V_R|}{V_0}$, where $V_R$ - voltage/stress between the reflector and the cathode, designed taking into account the action of space charge.

Disregarding interception of electrons by grid of gap with their output from decelerating field, it is possible to count $I_R \approx I$ and respectively $\delta I_R(t) \approx \delta I(t)$. since in (1.46) relation $\delta I_R(t) \bar{I}_R$ . stands, then error will affect only the fluctuations of current distribution, just as during the computation of the fluctuations of electronic conductivities.

Total fluctuations of transit angle are equal to

$$\delta\theta(t) = \delta\theta_v(t) + \delta\theta_i(t) = \bar{\theta} \, \frac{\delta v_0(t)}{\bar{v}_0} - 2\bar{\theta} F_J \, \frac{\delta I(t)}{\bar{I}} \, . \quad (1.47)$$
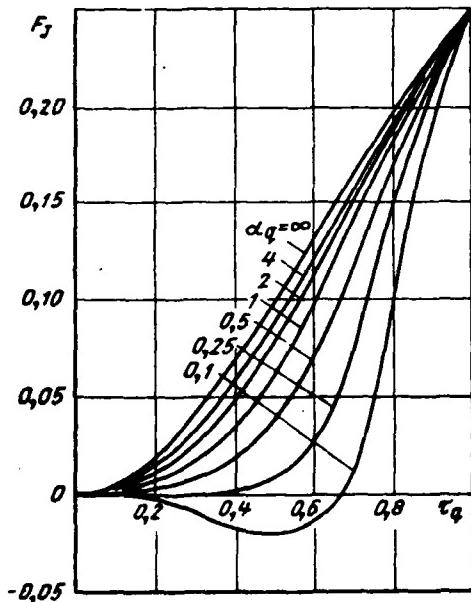
Fig. 1.9.  Dependence of function $F_J$ on parameter $\tau_q$ at different values of parameter $\alpha_q$.

Page 43.

After substitution of obtained values $\delta I(t)$, $\delta g(t)$, $\delta b(t)$, $\delta\theta(t)$ in (1.39), we will obtain

$$
\begin{aligned}
\frac{\partial U(t)}{\overline{U}} &= \frac{J_1(\overline{X})}{\overline{X}J_2(\overline{X})} \left\{ \left(1 - \frac{\overline{g}_e}{\overline{g}} + 2\overline{\theta}F_J \operatorname{tg} \overline{\Delta\theta}\right) \left[\frac{\delta I_{\text{вр}}(t)}{\overline{I}_{\text{к}}} + \right.\right.\\
&\quad + \frac{\delta I_J(t)}{\overline{I}_{\text{к}}} + \frac{\delta I_\Phi(t)}{\overline{I}_{\text{к}}} + \frac{\delta I_\tau(t)}{\beta\overline{I}_{\text{к}}}\Bigg] + \\
&\quad + \frac{\overline{g}_{e2}'}{\overline{g}} \frac{\partial l_o'(t)}{\overline{I}_2'} + \frac{\overline{g}_{e2}'}{\overline{g}} \frac{\delta l_o'(t)}{\overline{I}_2'} - \overline{\theta} \operatorname{tg} \overline{\Delta\theta} \frac{\delta v_0(t)}{\overline{v}_0}\Bigg\}, \\
\delta\omega(t) &= \frac{\overline{\omega}}{2Q_{\text{н}}} \left\{ \left(-\frac{\overline{b}_e}{\overline{g}} - \frac{\overline{g}_e}{\overline{g}} \operatorname{tg} \overline{\Delta\theta} + \frac{2\overline{\theta}\overline{F}_J}{\cos^2\overline{\Delta\theta}}\right) \times \right.\\
&\quad \times \left[\frac{\delta I_{\text{вр}}(t)}{\overline{I}_{\text{к}}} + \frac{\delta I_J(t)}{\overline{I}_{\text{к}}} + \frac{\delta I_\Phi(t)}{\overline{I}_{\text{к}}} + \frac{\delta I_\tau(t)}{\beta\overline{I}_{\text{к}}}\right] - \\
&\quad - \frac{\overline{b}_{e2}'}{\overline{g}} \frac{\delta l_o'(t)}{\overline{I}_2'} - \frac{\overline{b}_{e2}'}{\overline{g}} \frac{\delta l_o'(t)}{\overline{I}_2'} - \frac{\overline{\theta}}{\cos^2\overline{\Delta\theta}} \frac{\delta v_0(t)}{v_0}\Bigg\}.
\end{aligned}
\tag{1.48}
$$

These formulas represent $\delta U(t)/\bar{U}$ and $\delta\omega(t)$ in the form of sums, whose components are determined by independent random physical processes. It is known that the mean square of the sum of the independent random processes is equal to the sum of the mean squares of components. The same relates also to the spectral densities of the mean squares (see appendix 1).

Let us designate spectral density of mean square of relative fluctuations of amplitude $\delta U(t)/\bar{U}$ through $W_{au}(F)$, that of fluctuations of frequency $\delta f(t)=\delta\omega(t)/2\pi$ - through $W_{fu}(F)$. For the designation of the spectral densities of the mean squares of the fluctuations of currents, entering the right sides of expressions (1.48), we utilize the same indices, that they stand with the designation of fluctuations themselves. For example, to fluctuation $\delta I_{\phi}(t)$ corresponds spectral density $W_{\phi}(F)$, fluctuation $\delta i'_{\theta}(t)$ - spectral density $W'_{\theta}(F)$.

Page 44.

Then

$$W_{au}(F) = \left[\frac{J_1(\bar{X})}{\bar{X}J_2(\bar{X})}\right]^2 \left\{\left(1 - \frac{\bar{g}_t}{g} + 2\bar{\delta}F_J\,\mathrm{tg}\,\Delta\bar{\theta}\right)^2 \times\right.$$

$$\times \left[\frac{W_{ap}(F)}{(\bar{I}_u)^2} + \frac{W_J(F)}{(\bar{I}_u)^2} + \frac{W_{\phi}(F)}{(\bar{I}_u)^2} + \frac{W_\tau(F)}{(\beta\bar{I}_u)^2}\right] +$$

$$\left. + \left(\frac{\bar{g}_{e2}}{g_e}\right)^2 \frac{W'_{\theta}(F)}{(\bar{I}'_2)^2} + \left(\frac{\bar{g}_{e2}}{g_e}\right)^2 \frac{W'_{\theta}(F)}{(\bar{I}'_2)^2} + \bar{\theta}^2\,\mathrm{tg}^2\overline{\Delta\theta}\,\frac{W_v(F)}{(\bar{v}_0)^2}\right\},$$

$$W_{f_H}(F) = \left(\frac{\overline{f}}{2Q_H}\right)^2 \left\{ \left(\frac{\overline{b_e}}{g} + \frac{\overline{g_e}}{g}\, tg\, \overline{\Delta\theta} - \frac{2\overline{\theta}\, F_J}{\cos^2 \overline{\Delta\theta}}\right)^2 \times \right.$$

$$\times \left[\frac{W_{\mathrm{ap}}(F)}{(\overline{I_K})^2} + \frac{W_J(F)}{(\overline{I_K})^2} + \frac{W_\Phi(F)}{(\overline{I_K})^2} + \frac{W_\tau(F)}{(\beta \overline{I_K})^2}\right] +$$

$$+ \left(\frac{\overline{b'_{e2}}}{g}\right)^2 \frac{W'_3(F)}{(\overline{I'_2})^2} + \left(\frac{\overline{b'_{e2}}}{g}\right)^2 \frac{W'_\sigma(F)}{(\overline{I'_2})^2} + \frac{\overline{\theta^2}}{\cos^4 \overline{\Delta\theta}}\, \frac{W_v(F)}{(\overline{v_0})^2} \right\} \cdot \text{(1.49)}$$

Spectral densities $W_{\mathrm{ap}}(F)$, $W_J(F)$, $W_\tau(F)$, $W'_\sigma(F)$, $W_v(F)$   are

rated/estimated with the aid of formulas (1.15), (1.20), (1.21),

(1.22) and (1.24), given in S 2.  The spectral density of flicker

noise of the cathode current can be determined now only

experimentally.  In S 2 it was indicated that in the noises of the

secondary emission and current distribution the flicker effect also

can be developed.  Therefore at the sufficiently low frequencies the

true values of spectral densities $W_\tau(F)$ and $W'_\sigma(F)$ can prove to be

higher than calculated by formulas (1.22) and (1.24).  The information

about flicker-components of spectral densities also can be obtained

only from the experiment.


In conclusion let us pause at effect of transient processes,

which could not be taken into consideration within the framework of

quasi-static method used for conclusion/output of expressions (1.49).

The analysis, based on the solution of the differential equations of

generator with the method of the slowly changing amplitudes, shows

that in the case of optimum transit angle ($\overline{\Delta\theta}=0$) the transient

processes influence the fluctuation of amplitude ' only, decreasing

value $W_a(F)$ proportional to coefficient of p, equal to

$$p = \frac{1}{1 + \left[ 2Q_{\text{н}} \dfrac{F}{\bar{f}} \dfrac{J_1(\bar{X})}{\bar{X} J_2(\bar{X})} \right]^2}$$                (1.50)

FOOTNOTE [1]. With $\overrightarrow{\Delta\theta} \neq 0$ transient processes have certain effect also on spectrum $W_f(F)$. ENDFOOTNOTE.

If we multiply $W_{a_\text{н}}(F)$ by this coefficient, then it is possible to design level of spectral density of fluctuations of amplitude, also, at frequencies, which exceed in value passband of resonator. This is of interest during the evaluation/estimate of the noises, introduced by klystron – the heterodyne of superheterodyne radio receiver.

Page 45.

Expression (1.50) makes it possible to formulate applicability condition for quasi-static formulas (1.49):

$$\left[ 2Q_{\text{н}} \frac{F_{\text{макс}}}{\bar{f}} \frac{J_1(\bar{X})}{\bar{X} J_2(\bar{X})} \right]^2 \ll 1.$$

If we consider that during computation $W_a(F)$ the error, which exceeds 1 dB, is not admitted, then latter/last condition will be rewritten as follows:

$$\left[ 2Q_{\text{н}} \frac{F_{\text{макс}}}{\bar{f}} \frac{J_1(\bar{X})}{\bar{X} J_2(\bar{X})} \right]^2 < 0,26;$$

whence

$$F_{макс} \leqslant 0{,}26 \frac{\overline{X} J_2(\overline{X})}{J_1(\overline{X})} \Delta f \qquad (1.51)$$

(here) $\Delta f$ - passband of resonator).

In energetically effective mode/conditions of generator $\overline{X}=1.84$, i.e. it is final

$$F_{макс} \leqslant 0{,}26 \, \Delta f. \qquad (1.52)$$

With $\overline{\Delta\theta} \neq 0$ or with decrease $\overline{X}$ - due to a change in the mode/conditions of klystron on the load or according to the feed evaluation/estimate $F_{макс}$ becomes more rigid.

3.2.  Fluctuations, called by the shf/SVCh noises of electronic flux.

Besides low-frequency noises, on amplitude and frequency of klystron act spectral components of shf noises of electronic flux, oscillation frequencies localized in vicinity.  Their action consists in the fact that they produce random changes in amplitude and phase of the current, induced in resonator gap.  As it will be shown below, this leads to the fluctuations of amplitude and frequency of the generatable.  The low value of noises makes it possible to assume that spectral components of fluctuations at a certain frequency $\Omega$ are formed as a result of acting spectral components of noise at frequencies $\overline{\omega}+\Omega$ and $\overline{\omega}-\Omega$ similarly how this occurs in the case of detection of the weakly modulated oscillation or sum of harmonic

oscillation and small on the noise level.

Since we are interested in limited frequency band of fluctuations $(\Omega < \Omega_{\text{макс}} \ll \bar{\omega})$, fact indicated makes it possible to examine only action of narrow region of the spectrum of noise, whose width $2\Omega_{\text{макс}} \ll \bar{\omega}$.

Page 46.

From theory of random processes it is known that narrow-band random process of x(t) can be represented in the form of oscillation with those slowly changing by amplitude and phase:
x(t)=a(t)cosω₁t+b(t)sinω₁(t)=C(t)cos[ω₁t-φ(t)], where $\omega_1$ - medium frequency of noise spectrum.

It is sometimes convenient to examine narrow-band random process in complex form:

$$z(t) = C(t) e^{j[\omega_1 t - \varphi(t)]}. \qquad (1.53)$$

It is obvious that x(t)=Reż(t).

Spectra of mean squares of slowly changing functions a(t)=C(t)cosφ(t) and b(t)=C(t)sinφ(t) are connected with spectrum of mean square of noise x(t) as follows:

$$W_a(F) = W_b(F) = W_x(f_1 - F) + W_x(f_1 + F), \qquad (1.54)$$

where $f_1 = \dfrac{\omega_1}{2\pi}$, $F = \dfrac{\Omega}{2\pi}$. Let us note also that functions a(t) and b(t) are

not correlated [25].

We will use relationship/ratio (1.53) for representation of noise current, induced at grids of resonator gap; medium frequency of selected narrow section of noise spectrum let us take as equal to oscillation frequency $(\omega_1=\omega)$:

$$i_{\text{ш}}(t) = C(t)\, e^{j[\omega t - \varphi(t)]}. \qquad (1.55)$$

The complete induced current is equal to sum $i_{\text{н}\Sigma}(t) = I_{\text{н}}(t) + i_{\text{ш}}(t)$. In accordance with (1.30) $I_{\text{н}}(t) = I_{\text{н}} e^{j(\omega t - \theta)}$, where $I_{\text{н}} = 2MIJ_1(MU\theta/2V_0)$. After taking this into consideration, let us rewrite $i_{\text{н}\Sigma}(t)$ as follows:

$$i_{\text{н}\Sigma}(t) = I_{\text{н}}\left\{ 1 + \frac{C(t)\, e^{-j[\varphi(t) - \theta]}}{I_{\text{н}}} \right\} e^{j(\omega t - \theta)}.$$

Low value of noises makes it possible to consider that $\dfrac{C(t)}{I_{\text{н}}} \ll 1$. After using this, we will obtain

$$i_{\text{н}\Sigma}(t) \approx I_{\text{н}}\left\{ 1 + \frac{C(t)\cos[\varphi(t) - \theta]}{I_{\text{н}}} \right\} e^{j\left\{ \omega t - \theta - \frac{C(t)\sin[\varphi(t) - \theta]}{I_{\text{н}}} \right\}}.$$

It is hence evident that the action of shf noises is reduced to weak modulation of amplitude and phase of the induced current.

Page 47.

Since the modulating functions

$$\frac{C(t)\cos[\varphi(t) - \theta]}{I_{\text{н}}} \quad \text{and} \quad \frac{C(t)\sin[\varphi(t) - \theta]}{I_{\text{н}}}$$

- are slow, for the approximate determination of the fluctuations of
amplitude and frequency let us furthermore use the quasi-static
method:  it is possible to proceed from the equation of steady state
(1.33), and after replacing in it

$$i_{_H} = 2MIJ_1 \left( \frac{MU\theta}{2V_0} \right) \quad \text{на} \quad ^{(1)}$$

$$i_{_{H2}} = \left\{ 1 + \frac{C(t)\cos[\varphi(t) - \theta]}{2MIJ_1 \left( \frac{MU\theta}{2V_0} \right)} \right\} 2MIJ_1 \left( \frac{MU\theta}{2V_0} \right) \times$$

$$\times e^{-J\left\{ \theta + \frac{C(t)\sin[\varphi(t) - \theta]}{2MIJ_1\left( \frac{MU\theta}{2V_0} \right)} \right\}} \cdot$$

Key: (1).  by.

Assuming/setting $U=\bar{U}+\delta U(t)$, $\omega=\bar{\omega}+\delta\omega(t)$ and counting $\theta=\bar{\theta}$, $g=\bar{g}$, $I=\bar{I}$
constant/invariable, we will obtain equations, analogous (1.34), but
taking into account fluctuations:

$$\left.\begin{aligned}
&\bar{g}[\bar{U} + \delta U(t)] = \\
&= -\left\{ 1 + \frac{C(t)\cos[\varphi(t) - \bar{\theta}]}{2M\bar{I}J_1\left\{ \frac{M[\bar{U} + \delta U(t)]\bar{\theta}}{2V_0} \right\}} \right\} \times \\
&\times 2M\bar{I}J_1\left\{ \frac{M[\bar{U} + \delta U(t)]\bar{\theta}}{2V_0} \right\} \times \\
&\times \sin\left\{ \bar{\theta} + \frac{C(t)\sin[\varphi(t) - \bar{\theta}]}{2M\bar{I}J_1\left\{ \frac{M[\bar{U} + \delta U(t)]\bar{\theta}}{2V_0} \right\}} \right\}, \\
&[\bar{U} + \delta U(t)] 2C[\bar{\omega} + \delta\omega(t) - \omega_0] = \\
&= -\left\{ 1 + \frac{C(t)\cos[\varphi(t) - \bar{\theta}]}{2M\bar{I}J_1\left\{ \frac{M[\bar{U} + \delta U(t)]\bar{\theta}}{2V_0} \right\}} \right\} \times \\
&\times 2M\bar{I}J_1\left\{ \frac{M[\bar{U} + \delta U(t)]\bar{\theta}}{2V_0} \right\} \times \\
&\times \cos\left\{ \bar{\theta} + \frac{C(t)\sin[\varphi(t) - \bar{\theta}]}{2M\bar{I}J_1\left\{ \frac{M[\bar{U} + \delta U(t)]\bar{\theta}}{2V_0} \right\}} \right\}.
\end{aligned}\right\} \quad (1.56)$$

Page 48.

Average/mean values of parameters are connected with equations

$$\overline{g}\,\overline{U} = -2M\overline{I}J_1\left(\frac{M\overline{U}\,\overline{\theta}}{2V_0}\right)\sin\overline{\theta},$$

$$2C(\omega-\omega_0)\overline{U} = -2M\overline{I}J_1\left(\frac{M\overline{U}\,\overline{\theta}}{2V_0}\right)\cos\overline{\theta}. \qquad (1.57)$$

Linearizing equations (1.56) for fluctuation terms [46] and deducting of them appropriate equations (1.57), we find equations for fluctuations:

$$\overline{g}\,\partial U(t) = -2M\overline{I}J_1'(\overline{X})\,\overline{X}\,\sin\overline{\theta}\,\frac{\partial U(t)}{\overline{U}} - C(t)\cos[\varphi(t)-\overline{\theta}]\sin\overline{\theta} -$$

$$- C(t)\sin[\varphi(t)-\overline{\theta}]\cos\overline{\theta},$$

$$2C\overline{U}\,\partial\omega(t) + 2C(\overline{\omega}-\omega_0)\,\partial U(t) =$$

$$= -2M\overline{I}J_1'(\overline{X})\,\overline{X}\cos\overline{\theta}\,\frac{\partial U(t)}{\overline{U}} -$$

$$- C(t)\cos[\varphi(t)-\overline{\theta}]\cos\overline{\theta} + C(t)\sin[\varphi(t)-\overline{\theta}]\sin\overline{\theta}.$$

here $\overline{X}=M\overline{U}\overline{\theta}/2V_0$ - average bunching parameter. After the conversions, for which are used equations (1.57) and relationship/ratio, which escapes/ensues from recursion formulas for the Bessel functions: $J_1(\overline{X})-\overline{X}J_1'(\overline{X})=\overline{X}J_2(\overline{X})$, we will obtain we will obtain the expressions, which determine the relative fluctuations of amplitude and fluctuation of the angular frequency:

$$\frac{\delta U(t)}{\overline{U}} = \frac{C(t)\sin\varphi(t)}{2M\,\overline{I}\,\overline{X}J_2(\overline{X})\sin\overline{\theta}},$$
$$\delta\omega(t) = -\frac{\overline{g}}{2C}\frac{C(t)\cos\varphi(t)-\text{ctg}\,\overline{\theta}\,C(t)\sin\varphi(t)}{2M\overline{I}J_1(\overline{X})}. \qquad \left.\begin{matrix}\\\\\end{matrix}\right\} \quad (1.58)$$

Let us note that in latter/last formulas slow functions

$a(t)=C(t)\cos\varphi(t)$ and $b(t)=C(t)\sin\varphi(t)$ figure. The spectral densities

of their average/mean squares are expressed by the spectral density of

the mean square of the noise, which these functions present (in our

case - induced noise current). In accordance with (1.54)

$$W_a(F) = W_b(F) = W_{iн}(\overline{f}-F) + W_{iн}(\overline{f}+F), \qquad (1.59)$$

where $W_{iн}(\overline{f}\pm F)$ - the spectral density of the mean square shf noise

current, induced at the grids of gap.

Page 49.

Let us replace in (1.58) fluctuation of angular frequency $\delta\omega(t)$

by $\delta f(t)=\delta\omega(t)/2\pi$. Let us consider also that $\overline{I}$ is the average/mean

current of the electrons reflected in the gap and is expressed by

formula (1.31): $\overline{I}=\beta\overline{I}_\kappa$, where $\overline{I}_\kappa$ - average/mean current of cathode.

This makes it possible to rewrite formulas (1.58) as follows:

$$\frac{\delta U(t)}{\overline{U}} = \frac{b(t)}{2M\beta\overline{I}_\kappa\,XJ_2(\overline{X})\,\cos\overline{\Delta\theta}},$$
$$\delta f(t) = -\frac{\overline{f}}{2Q_н}\frac{a(t)+\text{tg}\,\overline{\Delta\theta}\,b(t)}{2M\beta\overline{I}_\kappa J_1(\overline{X})\cos\overline{\Delta\theta}}, \qquad \left.\begin{matrix}\\\\\end{matrix}\right\} \quad (1.60)$$

where $\overline{\Delta\theta}=\overline{\theta}-2\pi(N+3/4)$ - divergence of the mean angle of the flight/span

of electrons in the decelerating field from its optimum value, and

$Q_н = \dfrac{\omega_0 C}{\overline{g}} \approx \dfrac{\overline{\omega}C}{\overline{g}}$ - quality of the loaded resonator.

Since functions a(t) and b(t) are not correlated, from (1.59) and (1.60) we get following expressions for spectral densities of mean squares of relative fluctuations of amplitude $W_{ab}(F)$ and fluctuations of frequency $W_{fb}(F)$:

$$W_{ab}(F) = \frac{W_{iu}(\bar{f}-F) + W_{iu}(\bar{f}+F)}{[2M\beta\bar{I}_k\,\bar{X}J_2(\bar{X})]^2\cos^2\overline{\Delta\theta}} ,$$

$$W_{fb}(F) = \left(\frac{\bar{f}}{2Q_u}\right)^2 \frac{[W_{iu}(\bar{f}-F) + W_{iu}(\bar{f}+F)](1+\text{tg}^2\overline{\Delta\theta})}{[2M\beta\bar{I}_k J_1(\bar{X})]^2\cos^2\overline{\Delta\theta}} .$$

(Index «B» it indicates the high-frequency origin of fluctuations).

It is expressed spectral density of induced noise current through spectral density of convection: $W_{iu}(\bar{f}\pm F) = M^2 W_i(\bar{f}\pm F)$, where M - coefficient of electronic interaction, and $W_i(\bar{f}\pm F)$ - spectral density of mean square shf noise in convection current, which penetrates gap between resonator grids. Since $F_{uakc} \ll \bar{f}$, approximately it is possible to consider that $W_{iu}(\bar{f}\pm F) \approx M^2 W_i(\bar{f})$. Taking this into account

$$W_{ab}(F) = \frac{W_i(\bar{f})}{2\beta^2\bar{I}_k^2[\bar{X}J_2(\bar{X})]^2\cos^2\overline{\Delta\theta}} , \quad \left.\begin{array}{c}\\\\\end{array}\right\}$$

$$W_{fb}(F) = \left(\frac{\bar{f}}{2Q_u}\right)^2 \frac{(1+\text{tg}^2\overline{\Delta\theta})W_i(\bar{f})}{2\beta^2\bar{I}_k^2 J_1^2(\bar{X})\cos^2\overline{\Delta\theta}} . \quad (1.61)$$

Page 50.

Until now, was not discussed question, that is convection noise current in gap between resonator grids, which is source of induced noise. This current is formed by the electrons, which move to the

opposite sides - to the reflector and from it.  Let us assume that the spectral noise density in the convection current, which intersects gap during the motion to reflector $W_i'(\bar{f})$ is known to us.For the brevity we will call this current "straight line", and the current of the electrons - "reverse/inverse reflected".  Thus, $W_i'(\bar{f})$ represents with spectral noise density in the forward current.  In light of the aforesaid above, for calculating the fluctuations of oscillation/vibration is sufficient to know $W_i'(\bar{f})$ only in the vicinity of oscillation frequency, i.e., to know $W_i'(\bar{f} + F) \approx W_i'(\bar{f})$.

Noise also induces reverse convection current at grids of gap; at the given instant t noises in inverse current are determined by noises in forward current at preceded moment of time $t - T_0$, where $T_0$ - mean electron transit time in decelerating field.  As a result, all spectral components in inverse current are out of phase with respect to appropriate components in the forward current.  In contrast to the forward current, which contains only constant and noise components inverse current it contains also basic and higher harmonics of the generatable oscillation/vibration.  The highest harmonics appear in it as a result of the nonlinearity of the process of grouping; it leads also nonlinearity to a change in the spectral composition of noise due to the combination effects (mixing of the frequencies of noise components and the harmonic frequencies of the generatable oscillation/vibration, which plays the role of heterodyne).

Thus, for example, third harmonic of oscillation/vibration,

mixing with component of noise, whose frequency is close to frequency of second harmonic, is formed supplementary noise of difference frequency, close to fundamental frequency. Similarly spectral components of noises near the fundamental frequency are transferred into the vicinity of harmonic frequencies with the formation/education of summation combination frequencies. With such phenomena we collide in any nonlinear system, for example in the mixer of superheterodyne radio receiver.

Page 51.

As a result of combination mixing of frequencies of fluctuations spectral density of noise convection current of electrons reflected near oscillation frequency $\bar{f}$ proves to be spectral density function of noise of straight/direct convection current near frequencies of all harmonics of oscillation/vibration:

$$W_i^? (\bar{f}) = \sum_{n=1}^{n=\infty} r_n W_i^? (n\bar{f}), \qquad (1.62)$$

where $r_n$ - coefficients, which depend on amplitudes of harmonics, interaction with which withstands fluctuations from vicinity of frequencies $n\bar{f}$ into vicinity of oscillation frequency $\bar{f}$.

In order to determine spectral density of average square of complete noise of convection current in gap, cannot be simply accumulated $W_i^? (\bar{f})$ and $W_i^? (\bar{f})$, since fluctuations in straight/direct and inverse currents have common origin and one must take into account

their correlation.  The resulting noise depends on phase displacement in the decelerating field, i.e., in the final analysis, from the mean angle of the flight/span of electrons in the decelerating field $\bar{\theta}$. Let us note that the combination effects weaken/attenuate the correlation of noises in straight/direct and inverse currents, since in the noises of inverse current the components, transferred into the vicinity of frequency $\bar{f}$ from other regions of the spectrum, are present.

During conclusion/output (1.61) combination effects were not taken into consideration.  It is possible to show that they are not too strongly are not manifested at the level of spectral noise density in inverse current, changing it by no more than 3 dB.  Therefore $W_i^{\cdot}(\bar{f})$ always remains the value of the same order as $W_i^{\cdot}(\dot{f})$ and it is possible to utilize (1.61) for the evaluation/estimate of the levels of fluctuations, after assuming $W_i^{\cdot}(\bar{f}) = W_i^{\cdot}(\dot{f})$.

In [26] are given expressions for $W_{o\cdot}(F)$  and $W_{f\cdot}(F)$, obtained taking into account of transient processes and combination conversion of noises with grouping.

Page 52.

During their conclusion/output were also taken in the attention to the fluctuation of the average speed of electrons of shf range, the forming as a result of grouping supplementary noises in the current of the electrons reflected; these expressions are reproduced below for

the case $\overline{\Delta\theta}=0$ (work in the center of the zone of generation):

$$W_{as}(F) = \cfrac{\Phi_{al}\cfrac{W_i(\overline{f})}{I_0^2}+\overline{\theta}^2\Phi_{av}\cfrac{W_v(\overline{f})}{v_0^2}}{1+\left[\,2Q_H\cfrac{F}{\overline{f}}\cfrac{J_1(\overline{X})}{\overline{X}J_2(\overline{X})}\right]^2}\,,$$

$$W_{fs}(F) = \left(\cfrac{\overline{f}}{2Q_H}\right)^2\left[\Phi_{fl}\cfrac{W_i(\overline{f})}{I_0^2}+\overline{\theta}^2\Phi_{fv}\cfrac{W_v(\overline{f})}{v_0^2}\right],$$

(1.63)

where

$$\Phi_{al} = \cfrac{\cfrac{1}{\beta_3^4}+1-2J_1^2(\overline{X})+J_2(2\overline{X})}{2\,[\overline{X}J_2(\overline{X})]^2}\,,$$

$$\Phi_{av} = \cfrac{1-J_2(2\overline{X})}{2\,[\overline{X}J_2(\overline{X})]^2}\,,$$

$$\Phi_{fl} = \cfrac{\cfrac{1}{\beta_3^4}+1-J_2(2\overline{X})}{2J_1^2(\overline{X})}\,,$$

$$\Phi_{fv} = \cfrac{1+J_2(2\overline{X})}{2J_1^2(\overline{X})}$$

(1.64)

(plotted functions $\Phi_{al}$, $\Phi_{av}$, $\Phi_{fl}$, $\Phi_{fv}$ are given in Fig. 1.10, $I_0$ - the constant component of the forward current between the grids of gap [1]; $v_0$ - the average speed of electrons in the gap; $\beta_3$ - coefficient of transmission of the grid of the nearest to the reflector; $W_i(\overline{f})$ and $W_v(\overline{f})$ - the spectral densities of the mean squares of noise current and noise speed of straight/direct electronic flux in the gap.

FOOTNOTE [1]. Between currents $\overline{I}_K$, $\overline{I}$ and $\overline{I}_0$ there is a connection/communication: $I_0 = \beta_1\beta_2\overline{I}_K$, $\overline{I} = \beta\overline{I}_K - \beta_1\beta_2\beta_3^2\overline{I}_K$, where $\beta_1$, $\beta_2$, $\beta_3$ - coefficients of transmission of the grids of the klystron (numbering of grids it corresponds to Fig. 1.8). the constant component of inverse current $\overline{I}$ is expressed as the constant component of the straight line $I_0$ thus: $\overline{I} = \beta_3^2 I_0$. ENDFOOTNOTE.
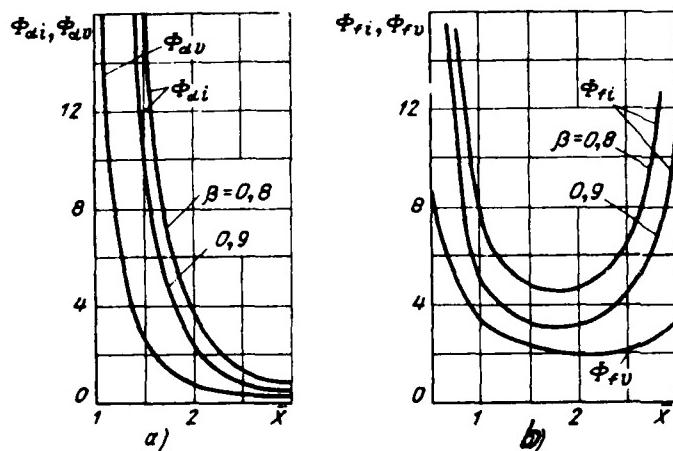
Fig. 1.10.  Dependence of functions $\Phi_{ai}$, $\Phi_{av}$ (a) and $\Phi_{fi}$, $\Phi_{fv}$ (b) on bunching parameter X at different values $\beta$.

Page 53.

During derivation of formulas (1.63) it was considered that values of spectral noise densities of current and speed do not depend on frequency, i.e.,  $W_i(n\bar{f}) = W_i(\bar{f})$, $W_v(n\bar{f}) = W_v(\bar{f})$.  This assumption made it possible to obtain simple expressions for  $W_{as}(F)$  and  $W_{fn}(F)$, not containing infinite sums.  Furthermore, during conclusion/output (1.63) is not taken into consideration the possible correlation between the noises of current and speed.  After leaving thus far in the side a question about the admissibility of these simplifications, let us pause at the determination of the noise spectra of shf current from speed  $W_i(\bar{f})$  and  $W_v(\bar{f})$, spectra of fluctuations  $W_{as}(F)$  and  $W_{fn}(F)$, necessary for the calculation

In §2 it was indicated that level of shf noises in electronic

fluxes of low-voltage klystrons at present cannot be reliably designed due to strong effect of surplus noise source. Therefore it is necessary to be turned to the experiment. Since the field of the gap, overlapped by grids, closely to the uniform, the induced noise current is determined to a considerable degree by the noise convection current of the waves of fundamental type space charge. This makes it possible to construct the procedure of experiment on expressions (1.28). Passing from the squares of the trigonometric functions, which are contained in (1.28), to the functions of dual angle and by expressing initial spectral densities $W_v(\omega, 0), W_i(\omega, 0)$ and $W_{iv}(\omega, 0)$ with the values of the spectral densities of convection noise current in maximum and minimum of its standing wave $W_{i\,макс}$ and $W_{i\,мин}$, it is possible to rewrite (1.28) in the following form:

$$
\left.
\begin{aligned}
W_v(\omega, \ x) &= \left(\frac{\omega_p}{\omega} \ \frac{v_0}{I_0}\right)^2 W_0\left[1 + K\cos^2\frac{\omega_p(x - x_m)}{v_0}\right], \\
W_i(\omega, \ x) &= W_0\left[1 - K\cos^2\frac{\omega_p(x - x_m)}{v_0}\right], \\
\operatorname{Im} W_{iv}(\omega, \ x) &= -\frac{\omega_p}{\omega} \ \frac{v_0}{I_0} W_0 K\sin^2\frac{\omega_p(x - x_m)}{v_0}, \\
\operatorname{Re} W_{iv}(\omega, \ x) &= \operatorname{Re} W_{iv}(\omega, 0),
\end{aligned}
\right\}
\quad (1.65)
$$

where

$$
W_0 = \frac{W_{i\,макс} + W_{i\,мин}}{2}, \quad K = \frac{W_{i\,макс} - W_{i\,мин}}{W_{i\,макс} + W_{i\,мин}}
$$

- parameters, which characterize average/mean level and spread/scope of the standing wave of the spectral density of noise current, while $x_m$ the coordinate of the nearest to the section in question minimum.

Page 54.

From expression (1.65), it follows that after determining is experimental (with the aid of movable resonator) $W_{i\,\text{макс}}$, $W_{i\,\text{мин}}$, $x_m$    and knowing average parameters of ray/beam $I_0$, $v_0$, $\omega_p$, we obtain complete information not only about $W_i(\omega, x)$, but also about $W_v(\omega, x)$ and Im $W_{iv}(\omega, x)$. For determination Re $W_{iv}(\omega, x)$ it is necessary to run correlation type supplementary test.

Unfortunately, experiments of this type require production of special technologically complicated mock-ups, which is justified far from always.  Furthermore, in a number of cases the length of the electrostatically focused low-voltage rays/beams is lower than half of the length of noise wave.

Most frequently only possibility is measurement of power of noise in resonator of klystron with positive repeller voltage [1], according to which can be designed spectral density of noise current in section of resonator.

FOOTNOTE [1].  Positive voltage/stress on the reflector is necessary in order to get rid of the effect of the flow of the electrons reflected. ENDFOOTNOTE.

The spectral density of the fluctuations of speed can be evaluated in this case only with weak change $W'_i(\omega, x)$ along the ray/beam, i.e., when $W_{i\,\text{макс}} \approx W_{i\,\text{мин}}$. From equations (1.65) it follows that with satisfaction of the condition Im $W'_{iv} \approx 0$ and
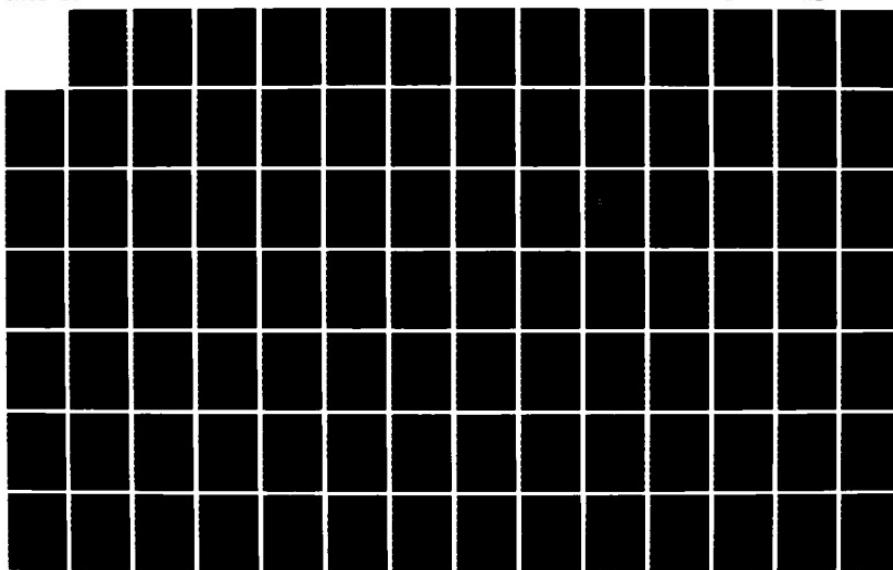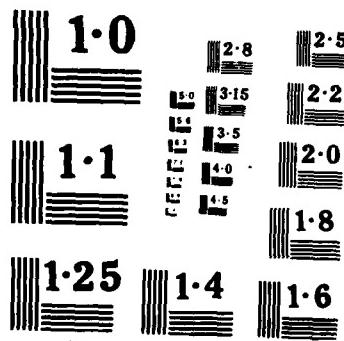
$$W_v(\omega) \approx \left(\frac{\omega_p}{\omega} \frac{v_0}{I_0}\right)^2 W_i(\omega) \qquad (1.66)$$

indicated.

Indirect indication of weak change $W_i(\omega, x)$ along ray/beam is high level of surplus noises, since action of uncorrelated noise sources must together with increase in level $W_i(\omega, x)$ weaken/attenuate its dependence on coordinate.

Measurements show that in low-voltage reflex klystrons of short-wave part of centimeter wave band level of noise current, as a rule is close in order to complete shot, which makes it possible to count use (1.66) by possible. Let us emphasize that formula (1.66) has a character of evaluation/estimate, which sometimes can be sufficiently rough. For the strongly noisy flow this evaluation/estimate is more realistic than calculation $W_v(\omega)$ according to the initial noise state of ray/beam on the cathode, since measured value $W_i(\omega)$ in formula (1.66) considers the action of all surplus noise sources in the electron stream.

Now let us pause at validity of assumptions about low value of correlation between noises of current and speed and uniformity of their spectra; accepted during conclusion/output (1.63).

Page 55.

it is not difficult to see that they nearest of all to the reality on

the high level of the surplus noise:  from (1.65) it follows that when $W_{i\,\text{макс}} \approx W_{i\,\text{мин}}$ value Im $W_{iv} \sim 0$; whereas value Re $W_{iv}$ is small even in the absence of surplus noises.  As far as the assumption about the uniformity of spectrum $W_i(\omega)$ [i.e. when $W_i(n\omega) \approx W_i(\omega)$], is concerned it approaches reality, if level $W_i(\omega)$ is close to the complete shot. However, from (1.66) it follows that when $W_i = \text{const}$ value $W'_v \sim 1/\omega^2$. This means that formulas (1.63) somewhat exaggerate the effect of the combination effects, connected with the fluctuations of speed.  The refinement of calculations hardly makes sense, since we have available only the rough estimate of level $W_v(\omega)$.

In conclusion let us note that with $\overline{\Delta\theta}=0$ transient processes, caused by time constant of resonator, just as in the case of fluctuations of low-frequency origin, they affect only value $W_{\text{ка}}(F)$. The comparison of formulas (1.63) with (1.49) and (1.50) shows that this effect is equal.  Consequently, the possibility of using the simplified formula for calculation $W_{\text{ка}}(F)$ (possibility of neglect of term $\left[ 2Q_{\text{н}}\dfrac{F}{\overline{f}} \dfrac{J_1(\overline{X})}{\overline{X}\,J_2(\overline{X})} \right]^2$ in the denominator), is given by formula (1.52).

3.3.  Role of different noise sources in the formation/education of the fluctuations of oscillation/vibration in the range of Doppler frequencies.

In view of the fact that noise sources of different spectral origin operate independently, complete spectra of fluctuations are located by addition:

$$W_a(F) = W_{an}(F) + W_{as}(F),$$
$$W_f(F) = W_{fn}(F) + W_{fs}(F). \qquad (1.67)$$

As a rule range of Doppler frequencies it is considerably
narrower than passband of resonator, which makes it possible to design
spectra of fluctuations without taking into account effect of
transient processes, i.e.  to disregard term $\left[ 2Q_a \dfrac{F}{f} \dfrac{J_1(\overline{X})}{\overline{X}J_2(\overline{X})} \right]^2$ in
denominators of expressions for $W_{as}(F)$ and $W_{as}(F)$. In this case spectra
$W_{as}$ and $W_{fs}$ are uniform, i.e., do not depend on frequency, while in
$W_{an}(F)$ and $W_{fn}(F)$ to be contained uniform, so frequency dependent
component, moreover the latter is caused only by flicker effect.

Page 56.

The typical spectra of the mean squares of the fluctuations of the
oscillation/vibration of reflex klystron in the range of Doppler
frequencies are given in Fig. 1.11.  In the spectra uniform component
and flicker- component clearly are distinguished.

Let us attempt to explain role of different noise sources in
formation/education of these components of spectra of fluctuations.

Let us conduct rough estimates, on the basis of typical
parameters of reflex klystron of short- wave part of centimeter wave
band, which works in center of zone of oscillations ($\overline{\Delta\theta}=0$) with
$\overline{X}=1.84$, which corresponds to effective energy mode/conditions.  The
parameters of klystron $I_x=25$ mA, $V_a=300\ V$ , $f/Q_n=5\cdot 10^7$, $g=2\cdot 10^{-4}$  mho,

N=4 [to this it corresponds $\bar{\theta}=2\pi(N+3/4)\approx 30$], $\beta_1=\beta_2=\beta_3=0.8$, $\beta=0.41$, $\theta_{\kappa}=\pi/2$ ($\theta_{\kappa}$ - transit angle in the gap between the resonator grids). Besides these parameters it is necessary to know the secondary-emission coefficient of grids $\sigma$. Taking into account the pollution/contamination of their surface by the decomposition products of the oxide layer of cathode, let us accept $\bar{\sigma}=2$. Let us finally assign the characteristics of space charge of ray/beam, necessary for computing the components of the spectra of fluctuations, caused by the noises of the speed of electronic flux and by the fluctuations of the electron transit time in the decelerating field due to the pulsations of space charge between the reflector and the resonator.
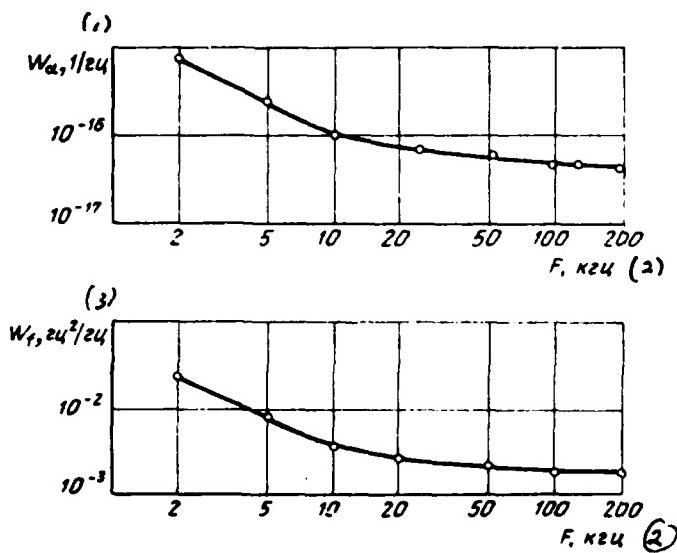
Fig. 1.11. Energy spectra of fluctuations of amplitude $W_a(F)$ and frequency $W_f(F)$ on logarithmic scale (klystron of range 3000 MHz, center of zone of generation).

Key: (1). 1/Hz (2). kHz. (3). Hz $^2$/Hz.

Page 57.

In the first case it is necessary to know $\omega_a/\omega$ - ratio of the natural vibration frequency of electronic plasma to the signal frequency in the section of drift (from the anode of gun to resonator gap), the secondly - value of function $F_J$, which depends on current density in the decelerating field. Let us accept $\omega_p/\omega = 0.02$, $F_J = 0.03$. These numerals are characteristic for the klystrons of the short-wave part of the range of microwaves; however, it is necessary to keep in mind that they can oscillate depending on the cross-sectional area of ray/beam.

Let us calculate forward current $I_0$ in gap secondary-electron currents $\bar{I}_2'$ and $\bar{I}_2'$, assuming that latter are created by electrons, dislodged/chased from internal surfaces of grids of gap:

$$I_0 = \beta_1 \beta_2 \bar{I}_{\kappa} = 16 \overset{(1)}{\textit{ma}}, \quad \bar{I}_2' = (1 - \beta_3) I_0 \,_{\vartheta} = 6{,}4 \overset{(2)}{\textit{ma}}, \quad \bar{I}_2' =$$
$$= (1 - \beta_2) \beta_3^2 I_0 \,_{\vartheta} = 4{,}1 \textit{ma}.$$

Key: (1). mA.

Now with the aid of formulas (1.42) and (1.43) it is possible to find the electronic conductivities:

$$\bar{g}_{e1}' = 0{,}43 \cdot 10^{-5} \overset{(1)}{\textit{mo}}, \qquad \bar{b}_{e1}' = 0{,}43 \cdot 10^{-5} \overset{(1)}{\textit{mo}},$$
$$\bar{g}_{e1}' = 0{,}34 \cdot 10^{-5} \textit{mo}, \qquad \bar{b}_{e1}' = 0{,}34 \cdot 10^{-5} \textit{mo},$$
$$\bar{g}_{e2}' = 0{,}88 \cdot 10^{-5} \textit{mo}, \qquad \bar{b}_{e2}' = -6{,}9 \cdot 10^{-5} \textit{mo},$$
$$\bar{g}_{e2}' = 0{,}56 \cdot 10^{-5} \textit{mo}, \qquad \bar{b}_{e2}' = -4{,}9 \cdot 10^{-5} \textit{mo}.$$

Key: (1). mho.

Complete electronic conductivities

$$\bar{g}_e = \bar{g}_{e1}' + \bar{g}_{e2}' + \bar{g}_{e1}' + \bar{g}_{e2}' = 2{,}2 \cdot 10^{-5} \overset{(1)}{\textit{mo}},$$
$$\bar{b}_e = \bar{b}_{e1}' + \bar{b}_{e2}' + \bar{b}_{e1}' + \bar{b}_{e2}' = -9{,}8 \cdot 10^{-5} \textit{mo}.$$

Key: (1). mho.

We see that active electronic conductivities, created by primary and secondary electrons, have identical order, in spite of the fact that secondary-electron currents are considerably less than primary-electronic. As far as susceptances are concerned, here effect of secondary-electron phenomena predominates: $|\bar{b}_{e2}'|$ by an order is more than $|\bar{b}_{e1}'|$.

Value of complete conductance $g = g_p + g_н + \bar{g}_e$ was accepted by equal to $2 \cdot 10^{-4}$ mho, which by an order exceeds $\bar{g}_e$. This relationship/ratio between g and $g_e$ is characteristic for the klystrons with the grids. The high value $\bar{g}$ is caused in essence by Joule losses (i.e. by high value $g_p$); value $g_н$ it is also great, since in the energetically advantageous conditions, connection with the load is established/installed so, in order to $\bar{g}_н \approx g_p + g_e$.

Page 58.

Carried out evaluations/estimates make it possible to somewhat simplify formulas (1.49) for $W_{aн}(F)$ and $W_{fн}(F)$:

1) since $\bar{g}_e / \bar{g} \ll 1$, that it is possible to accept $1 - \bar{g}_e \bar{g} \approx 1$;

2) ratio $\bar{g}'_{e2}/\bar{I}'_2$ and $b'_{e2}/\bar{I}'_2$ they do not depend on values $\bar{I}'_2$, since $\bar{g}'_{e2} \sim \bar{I}'_2$ and $\bar{b}'_{e2} \sim \bar{I}'_2$ [see formulas (1.43). Therefore it is possible to accept

$$\left(\frac{\bar{g}'_{e2}}{\bar{g}}\right)^2 \frac{W'_a}{(\bar{I}'_2)^2} + \left(\frac{\bar{g}'_{e2}}{\bar{g}}\right)^2 \frac{W'_a}{(\bar{I}'_2)^2} \approx \left(\frac{\bar{g}'_{e2}}{\bar{g}}\right)^2 \frac{W'_a + W'_a}{(\bar{I}'_2)^2}.$$

$$\left(\frac{\bar{b}'_{e2}}{\bar{g}}\right)^2 \frac{W'_a}{(\bar{I}'_2)^2} + \left(\frac{\bar{b}'_{e2}}{\bar{g}}\right)^2 \frac{W'_a}{(\bar{I}'_2)^2} \approx \left(\frac{\bar{b}'_{e2}}{\bar{g}}\right)^2 \frac{W'_a + W'_a}{(\bar{I}'_2)^2}.$$

Error, connected with this approximation/approach, does not exceed error in computation $W'_a$ and $W'_f$ according to formula (1.24) due to inaccuracy in determination of coefficients $\bar{\sigma}$ and H.

Taking into account aforesaid of formula for $W_{\alpha\mu}(F)$ and $W_{f\mu}(F)$ it is possible to rewrite as follows:

$$W_{\alpha\mu}(F) = \left[\frac{J_1(\overline{X})}{\overline{X}J_2(\overline{X})}\right]^2 \left[\frac{W_{xp}}{(\overline{I}_{\kappa})^2} + \frac{W_I}{(\overline{I}_{\kappa})^2} + \frac{W_{\Phi}}{(\overline{I}_{\mu})^2} + \right.$$

$$\left. + \frac{W_{\tau}}{(\beta\overline{I}_{\kappa})^2} + \left(\frac{\overline{g}'_{e2}}{\overline{g}}\right)^2 \frac{W'_{\sigma} + W'_{\sigma}}{(\overline{I}_2)^2}\right],$$

$$W_{f\mu}(F) = \left(\frac{\overline{f}}{2Q_{\mu}}\right)^2 \left\{\left(\frac{\overline{b}_e}{\overline{g}} - 2\overline{U}F_J\right)^2 \left[\frac{W_{xp}}{(\overline{I}_{\kappa})^2} + \right.\right.$$

$$\left.\left. + \frac{W_I}{(\overline{I}_{\kappa})^2} + \frac{W_{\Phi}}{(\overline{I}_{\mu})^2} + \frac{W_{\tau}}{(\beta\overline{I}_{\kappa})^2}\right] + \left(\frac{\overline{b}'_{e2}}{\overline{g}}\right)^2 \frac{W'_{\sigma} + W'_{\sigma}}{(\overline{I}'_2)^2}\right\}$$

(1.68)

Let us look first at uniform (independent of frequency) components of spectra of fluctuations.

Page 59.

Taking into account the made approximations/approaches and in accordance with (1.63), (1.67) and (1.68), and also (1.15), (1.20)-1.22), (1.24) and (1.66) these components can be recorded thus:

$$(W_{\alpha})_{p\text{авн}} = (W_{\alpha\mu})_i + (W_{\alpha\mu})_v + (W_{\alpha\mu})_{xp} + (W_{\alpha\mu})_J +$$

$$+ (W_{\alpha\mu})_{\tau} + (W_{\alpha\mu})_{\sigma}.$$

$$(W_f)_{p\text{авн}} = (W_{f\mu})_i + (W_{f\mu})_v + (W_{f\mu})_{xp} + (W_{f\mu})_J +$$

$$+ (W_{f\mu})_{\tau} + (W_{f\mu})_{\sigma} + (W_{f\mu})_{v'}$$

(1.69)

where

$$(W_{\alpha\mu})_i = \Phi_{\alpha i} \frac{W_i(\overline{f})}{I_0^2}; \quad (W_{\alpha\mu})_v = \overline{\vartheta}^2 \left(\frac{\omega_{\varrho}}{\omega}\right)^2 \Phi_{\alpha v} \frac{W_i(\overline{f})}{I_0^2};$$

$$(W_{\alpha H})_{xp} = \left[\frac{J_1(\overline{X})}{\overline{X} J_2(\overline{X})}\right]^2 \frac{2e \, \Gamma^2}{\overline{I}_\kappa} ;$$

$$(W_{\alpha H})_j = \left[\frac{J_1(\overline{X})}{\overline{X} J_2(\overline{X})}\right]^2 \frac{880 \, e \, I_{j\kappa} V \, \overline{V_0}}{(\overline{I}_\kappa)^2} ;$$

$$(W_{\alpha H})_T = \left[\frac{J_1(\overline{X})}{\overline{X} J_2(\overline{\lambda})}\right]^2 \frac{(1-\beta) 2e}{\beta \overline{I}_\kappa} ;$$

$$(W_{\alpha H})_e = \left[\frac{J_1(\overline{X})}{\overline{X} J_2(\overline{X})}\right]^2 \frac{2e(H-\sigma)(\overline{I}_2' + \overline{I}_2')}{(\overline{I}_2')^2} ;$$

$$(W_{f\,H})_i = \left(\frac{\overline{f}}{2 Q_H}\right)^2 \Phi_{fi} \frac{W_i(\overline{f})}{I_0^2} ;$$

$$(W_{f\,H})_v = \left(\frac{\overline{f}}{2 Q_H}\right)^2 \theta^2 \left(\frac{\omega_p}{\overline{\omega}}\right)^2 \Phi_{fv} \frac{W_i(\overline{f})}{I_0^2} ;$$

$$(W_{f\,H})_{xp} = \left(\frac{\overline{f}}{2 Q_H}\right)^2 \left(\frac{\overline{b}_e}{\overline{g}} - 2\overline{\theta} F_j\right)^2 \frac{2e \, \Gamma^2}{\overline{I}_\kappa} ;$$

$$(W_{f\,H})_j = \left(\frac{\overline{f}}{2 Q_H}\right)^2 \left(\frac{\overline{b}_e}{\overline{g}} - 2\overline{\theta} F_j\right)^2 \frac{880 \, e \, I_{j\kappa} V \, \overline{V_0}}{(\overline{I}_\kappa)^2} ;$$

$$(W_{f\,H})_T = \left(\frac{\overline{f}}{2 Q_H}\right)^2 \left(\frac{\overline{b}_e}{\overline{g}} - 2\overline{\theta} F_j\right)^2 \frac{(1-\beta) 2e}{\beta \overline{I}_\kappa} ;$$

$$(W_{f\,H})_e = \left(\frac{\overline{f}}{2 Q_H}\right)^2 \left(\frac{\overline{b}_{e2}'}{\overline{g}}\right)^2 \frac{2e(H-\sigma)(\overline{I}_2' + \overline{I}_2')}{(\overline{I}_2')^2} ;$$

$$(W_{f\,H})_v = \left(\frac{\overline{f}}{2 Q_H}\right)^2 \frac{(4-\pi)\overline{\theta}_\kappa^2 T_\kappa}{2 V_0 \overline{I}_\kappa} .$$

Page 60.

Formulas (1.69) represent $(W_\alpha)_{\text{полн}}$ and $(W_f)_{\text{полн}}$ in the form of sums of components/terms/addends, reflection effect of noise source of different physical origin. These components of the spectra of fluctuations are noted by the same indices, which were utilized earlier for the designation of the spectral noise densities, which excite the fluctuations: index "i" relates to the fluctuations,

caused by shf noises of the current of ray/beam, index " v" - by noises of the velocity of electrons. The value of remaining indices is such:   «др» it designates the fluctuations, caused by low-frequency shot noise, "j" - by ionic noise, «т» and "σ" - by noises of current distribution and secondary emission respectively.

Let us rate/estimate different components of spectra $(W_a)_{\text{p.um}}$ and $(W_f)_{\text{обвн}}$ on the basis of parameters of klystron given above.  in order this to make, it remains to assign level $W_i(\overline{j})$, temperature of cathode $T_к$, strength of ion current to cathode $I_{jк}$ and coefficient of the depression of shot noise at the low frequencies $\Gamma^2$.

Since calculation is performed for klystron of short-wave part of centimeter wave band, let us accept  $W_i(\overline{f}) = 2eI_0$ (level of complete shot noise; $\Gamma^2$ we will consider it equal to $10^{-2}$ (see §2), while $T_к = 1100°K$ (oxide cathode).  Let us accept the strength of ion current of cathode equal to $10^{-7}$ a (this numeral is undertaken according to the results of measuring the ion current of the reflector, which in the order is close to the ion current of cathode).

Values of components $(W_a)_{\text{pавн}}$ and $(W_f)_{\text{pавн}}$ designed according to given above data, are given in Tables 1 and 2.

As it follows from Table 1, level of fluctuations of amplitude with uniform spectrum is determined in essence by shf noises of current of ray/beam [(component) $(W_{aa})_i$].

Table 1.  components of the spectrum of the fluctuations of amplitude $(W_a)_{разн}$ [1/Hz].

| $(W_{ав})_i$ | $(W_{ав})_v$ | $(W_{ан})_{др}$ | $(W_{ан})_j$ | $(W_{ан})_т$ | $(W_{ан})_о$ |
|---|---|---|---|---|---|
| $10^{-16}$ | $2\cdot10^{-17}$ | $10^{-19}$ | $4\cdot10^{-19}$ | $2\cdot10^{-17}$ | $2\cdot10^{-19}$ |

Table 2.  The components of the spectrum of the fluctuations of frequency $(W_f)_{разн}$ [Hz+ $^2$/Hz].

| $(W_{fв})_i$ | $(W_{fв})_v$ | $(W_{fн})_{др}$ | $(W_{fн})_j$ | $(W_{fн})_о$ | $(W_{fн})_т$ | $(W_{fн})_v$ |
|---|---|---|---|---|---|---|
| $6\cdot10^{-3}$ | $2\cdot10^{-2}$ | $5\cdot10^{-4}$ | $2\cdot10^{-2}$ | $10^{-3}$ | $6\cdot10^{-2}$ | $5\cdot10^{-4}$ |

Page 61.

The contribution of the shf noises of speed on 7 dB is less.  Of the low- frequency noises most of all are developed the noises of current distribution; however, their even contribution on 7 dB is less than the contribution of shf noises of current.  The remaining low-frequency noise sources virtually are not manifested at the level $(W_a)_{разн}$.

In spectrum of fluctuation of frequency $(W_f)_{разн}$ (Table 2) most strongly are developed shf noises of current of ray/beam [component $(W_{fв})_i$] and low- frequency noises of current distribution and secondary emission [component $(W_{fн})_т$ and $(W_{fн})_о$]. An increase in the contribution of low-frequency noises in the fluctuation of frequency is caused by the high value reactive component secondary electronic conductivity of gap and by space-charge effect of ray/beam in the region of

decelerating field to the electron transit time.

Relationship/ratio between different components of spectra of fluctuations can be changed depending on mode of operation and parameters of klystron.  However, some conclusions, which follow from Tables 1 and 2, retain force over a wide range of a change in the parameters and mode/conditions, namely:

1) the level of the fluctuations of amplitude is defined in essence by shf noises of ray/beam;

2) the effect of low-frequency shot noises, low-frequency fluctuations of the initial velocity of electrons and noises of ionization is small both on the fluctuation of amplitude and on the fluctuation of frequency;

3) the level of the fluctuations of frequency is determined in essence by shf noises of ray/beam and by the low-frequency noises of current distribution and secondary emission.

Experiments, which were being carried out on klystrons of different types, confirm given evaluations/estimates and conclusions drawn on their foundation.  The quantitative disagreement of the measured and designed levels of fluctuations does not exceed one order.  With some results of comparison it is possible to become acquainted into [27].

Let us now move on to low-frequency fluctuations, excited by flicker effect.  Usually flicker effect is developed in the spectrum

of the fluctuations of frequency at frequencies of below 10 kHz, and
it is sometimes noticeable up to 50-100 kHz.  Since to calculate the
spectral density of flicker noise in the current of klystron is
impossible (see §2), then it is necessary to determine it
experimentally.  The low-frequency noise of cathode current is
measured according to diagram in Fig. 1.12 with the aid of the small
metallic resistor/resistance, connected with the unbranched part of
the circuit of power supply.

Page 62.

If we substitute value of measured spectral density of flicker
noise of cathode current $W_{\text{к}\phi}(F)$ into formulas for fluctuations and to
compare calculation with experiment, then in majority of cases
designed level of fluctuations of frequency will prove to be than
considerably lower measured.  Furthermore, experience often shows
incomplete, and in certain cases weak, the correlation of the flicker
noise of cathode current with the fluctuations of frequency.  This
means that the fluctuations of frequency are caused mainly by excess
flicker noise, which operates independent of the flicker noise of the
current of cathode.

Experimental confirmation of existence of excess flicker noise in
reflex klystrons can be obtained by measuring noise current in
external circuit of one of resonator grids (Fig. 1.13) [1].

FOOTNOTE [1].  Such an experiment easily to make on the klystrons,

intended for the work with the external resonator.  Upon the
examination/inspection of klystrons with the integral cavity it is
necessary to specially make mock-ups with the isolated/insulated grid.
ENDFOOTNOTE.

Its intensity, as a rule noticeably exceeds the level, which it would
be possible to ascribe to the action of the flicker noise of cathode
current.  The correlation of the flicker noises of the grid currents
and cathode is incomplete or is weak.  These facts can be explained
only by the existence of surplus flicker noise.


     In S2 it was indicated that this noise was connected with effects
of current distribution and secondary emission.  Therefore in the
expressions for flicker-component spectral densities of the
fluctuations of amplitude and frequency of the generatable should be
considered the action of the named effects.
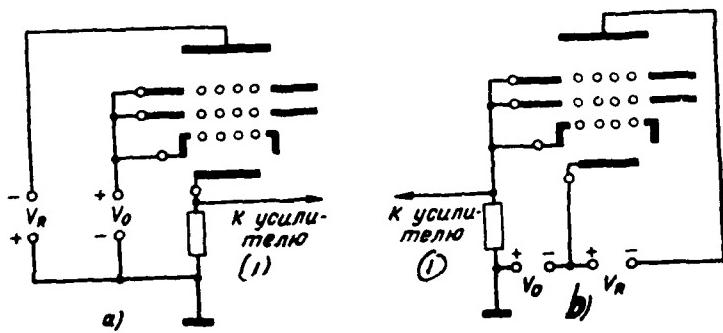
Fig. 1.12. Fundamental measuring circuit of fluctuations of current of cathode upon inclusion of measuring cathode resistor (a) and into unbranched section of circuit of positive electrodes (grids) (b).

Key: (1). To the amplifier.

Page 63.

On the basis of (1.49) and utilizing the same approximations/approaches, that also during conclusion/output (1.68), we will obtain:

$$(W_{s\,\text{и}})_\phi = \left[ \frac{J_1(\overline{X})}{\overline{X} J_2(\overline{X})} \right]^2 \left[ \frac{W_{\text{к}\phi}(F)}{(\overline{I}_\text{к})^2} + \frac{W_{\text{т}\phi}(F)}{(\beta\,\overline{I}_\text{к})^2} + \left( \frac{\overline{g}'_{\text{э}2}}{\overline{g}} \right)^2 \times \right.$$
$$\left. \times \frac{W'_{\text{э}\phi}(F) + W'_{\text{э}\phi}(F)}{(\overline{I}'_2)^2} \right], \qquad (1.70)$$

$$(W_{f\,\text{и}})_\phi = \left( \frac{\overline{f}}{2\,Q_\text{н}} \right)^2 \left\{ \left( \frac{\overline{b}_\text{э}}{\overline{g}} - 2\theta F_J \right)^2 \times \right.$$
$$\left. \left[ \frac{W_{\text{к}\phi}(F)}{(\overline{I}_\text{к})^2} + \frac{W_{\text{т}\phi}(F)}{(\beta\,\overline{I}_\text{к})^2} \right] + \left( \frac{\overline{b}'_{\text{э}2}}{\overline{g}} \right)^2 \frac{W'_{\text{э}\phi}(F) + W'_{\text{э}\phi}(F)}{(\overline{I}'_2)^2} \right\}. \qquad (1.71)$$

Index «φ» at spectral densities means that they all are connected with flicker effect.

For computation $(W_{c\text{я}})_\phi$ and $(W_{f\text{я}})_\phi$ it is necessary to know spectral densities of flicker noise of current of cathode $W_{\text{я}\phi}(F)$ and flicker noises of current distribution and secondary emission $W_{\text{т}\phi}(F)$ and $W_{\text{з}\phi}(F)$.

Spectral density of flicker noise of cathode $W_{\text{я}\phi}(F)$ is measured simply; for determination $W_{\text{т}\phi}(F)$ and $W_{\text{з}\phi}(F)$ it is necessary to utilize results of measurements of flicker noise in circuits of isolated/insulated grids. The interpretation of such measurements is not simple, and single-valued response/answer to a question, that causes in the specific case surplus noise in the circuit of grids - current distribution or the secondary emission - to obtain difficultly.

(1)

к усилителю

+ − + −
V$_g$     V$_R$
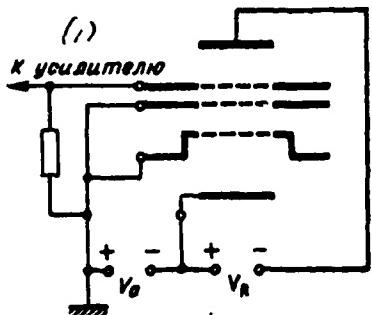
Fig. 1.13.   Fundamental measuring circuit of fluctuations of current of one of grids.

Key:  (1).  To the amplifier.

Page 64.

If we assume, that the excess flicker noise, measured in grid circuit, has secondary-electron origin, then it is possible to obtain satisfactory explanation of level observing in experiments of fluctuations of frequency.  The results of the comparison of the calculations, carried out on the basis of this hypothesis, with the experiment on the klystrons of s-band are given to [28].  A good coincidence was obtained, also, on the klystrons of the short-wave part of centimeter band.  In both cases a noticeable change in the level of flicker noise in the current of the isolated/insulated grid of klystron with a small change in its potential was indication of the role of the secondary emission.

However, all this does not prove exceptionally/exclusively

secondary-electron origin of surplus flicker noise.  Data sequence

obtained recently [1], definitely indicates that the part of the surplus

noise is connected with the effects of current distribution.


FOOTNOTE [1].   Jointly with V. A. Berdnikova.   ENDFOOTNOTE.


Flicker noise of current distribution acts on fluctuation of

amplitude, modulating operating current in gap of klystron [see

formula (1.70), and during fluctuation of frequency - modulating

density of space charge in region of reflector, i.e., time of transit

of electrons in decelerating field, and also modulating reactive/jet

electronic conductivity of resonator gap [formula (1.71)].  Since

reactive/jet electronic conductivity in essence is determined by

secondary-electron component, the manifestation of the flicker noise

of current distribution in the fluctuations of frequency is connected

with the strength of secondary-electron current in the gap.


Unfortunately, insufficient attention was paid to study of

physical nature of surplus flicker noise, and for its complete

understanding further investigations are required.  At present it is

possible to express only some assumptions about the mechanisms of its

formation/education.  Secondary-electron flicker noise can be

connected with the slow fluctuations of that averaged over the surface

of the grids of secondary-emission coefficient, which appear with a

change in the physicochemical properties of surface films on the grids

due to the transport phenomena of molecules and ions, which constantly

occur to working tube.

Flicker noise of current distribution can be connected with slow changes in form of ray/beam due to fluctuations of contact potential difference between surfaces of focusing electrode and cathode. The matched changes in the transverse initial velocities of the large groups of electrons under the effect of flicker-fluctuations of space charge in the pores of cathode can be another reason for its appearance.

Page 65.

3.4.   On the fluctuations in the span generator klystrons.

It is known that form of current pulses in span and reflex klystrons is identical. In both cases the grouped current is the delaying function of the voltage/stress, which modulates the velocity of electrons. This causes the resemblance of oscillating processes in the generators on span and reflex klystrons. Natural to expect the resemblance of their fluctuation characteristics.

Let us examine generator on span klystron with direct coupling between resonators (Fig. 1.1 ). If we consider coupling element ideal transformer with the mutual inductance factor $M_c$, then equivalent oscillator circuit can be represented then, as shown in Fig. 1.14.

From theory of span klystrons it is known (see S1), that

$$i_\mu = 2MI J_1(X) e^{-i\theta}. \qquad (1.72)$$

Expression (1.72) [1] is obtained under the assumption that grid voltage of the first (input) gap $u_1(t)=U_1\sin\omega t$, i.e., $\dot{U}_1=-jU_1$.

FOOTNOTE [1]. Expression for $i_M$ is recorded in the kinematic approximation/approach without taking into account longitudinal grouping. It is possible to show that neglect of this factor does not change the essence of the results of the analysis of the fluctuation parameters. ENDFOOTNOTE.

For calculations is convenient to convert diagram in Fig. 1.14, utilizing U-Shaped replacement scheme of transformer (Fig. 1.15), in which

$$\frac{1}{L_a} = \frac{L_2}{L_1 L_2 - M_c^2}, \quad \frac{1}{L_\beta} = \frac{M_c}{L_1 L_2 - M_c^2}, \quad \frac{1}{L_\gamma} = \frac{L_1}{L_1 L_2 - M_c^2}.$$
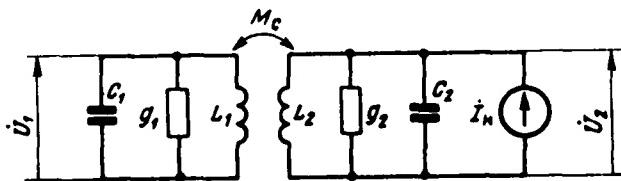
Fig. 1.14.   Equivalent oscillator circuit on span klystron:   $g_1$, $C_1$, $L_1$ and $g_2$, $C_2$, $L_2$ - equivalent parameters of first and second resonators according (taking into account external load), $I_н$ - current, induced at second pair of grids of klystron.
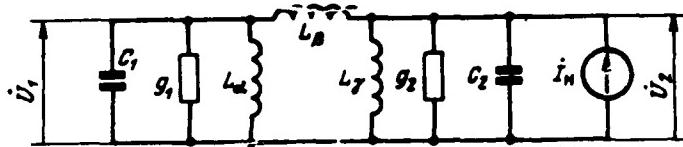


Fig. 1.15.   Converted oscillator circuit on span klystron.

Page 66.

Equations, which describe this diagram, look as follows:

$$\dot{U}_2 \left[ \left( g_1 + j\omega C_1 + \frac{1}{j\omega L_\alpha} + \frac{1}{j\omega L_\beta} \right) \times \right. $$
$$\left. \times \left( g_2 + j\omega C_2 + \frac{1}{j\omega L_\gamma} + \frac{1}{j\omega L_\beta} \right) - \left( \frac{1}{j\omega L_\beta} \right)^2 \right] =$$
$$= I_н \left( g_1 + j\omega C_1 + \frac{1}{j\omega L_\alpha} + \frac{1}{j\omega L_\beta} \right),$$
$$\dot{U}_1 \left[ \left( g_1 + j\omega C_1 + \frac{1}{j\omega L_\alpha} + \frac{1}{j\omega L_\beta} \right) \left( g_2 + j\omega C_2 + \right. \right.$$
$$\left. \left. + \frac{1}{j\omega L_\gamma} + \frac{1}{j\omega L_\beta} \right) - \left( \frac{1}{j\omega L_\beta} \right)^2 \right] = I_н \frac{1}{j\omega L_\beta}.$$

$$(1.73)$$

We will be restricted subsequently to special case, when

tunings/adjustings of resonators are close, and
connection/communication between them is considerably less than
critical. Latter/last condition is formulated as follows:

$$K_c^2 = \frac{M_c^2}{L_1 L_2} Q_1 Q_2 \ll 1,$$

where $K_c$ - generalized coupling coefficient, and $Q_1$, and $Q_2$ - partial
qualities of the resonators (designed taking into account
connections/communications with the external load of generator, which
it can be connected to any of the ducts/contours). Product $Q_1 Q_2 > 1$.
Consequently, $(M_c^2/L_1 L_2) \ll 1$, since $K_c^2 \ll 1$. In this approximation/approach

$$1/L_a \approx 1/L_1, \quad 1/L_T \approx 1/L_2, \quad 1/L_\beta \approx M_c/L_1 L_2.$$

Taking into account that the fact that $K_c^2$ and values of detunings
of resonators are low, it is possible to approximately convert
equations (1.73) and to record them in the following form:

$$\left. \begin{array}{l} \dot{U}_2 [g_2 + j \, 2 (\omega - \omega_{02}) C_2] = I_n, \\ \dot{U}_2 = \frac{j U_1}{\sqrt{g_1 g_2} K_c} [g_1 + {}^{\flat} (\omega - \omega_{01}) C_1]. \end{array} \right\} \qquad (1.74)$$

Here

$$\omega_{01} = 1/\sqrt{L_1 C_1} \quad and \quad \omega_{02} = 1 \sqrt{L_2 C_2}$$

- partial frequencies of resonators.

Page 67.

Substituting in (1.74)

$$\dot{U}_1 = -j U_1, \quad I_a = 2M \, j J_1 \left( \frac{M U_1 \theta}{2 V_a} \right) e^{-j\phi}, \quad \dot{U}_2 = U_2 e^{j\phi}$$

and dividing real and imaginary parts, we will obtain:

$$U_2 g_1 = 2MIJ_1 \left( \frac{MU_1 \theta}{2V_0} \right) \cos(\theta - \varphi),$$

$$U_2 2C_2(\omega - \omega_{02}) = -2MIJ_1 \left( \frac{MU_1 \theta}{2V_0} \right) \sin(\theta - \varphi),$$

$$U_2 \cos \varphi = \frac{U_1 g_1}{\sqrt{g_1 g_2} K_c},$$

$$U_2 \sin \varphi = \frac{U_1 2C_1(\omega - \omega_{01})}{\sqrt{g_1 g_2} K_c}.$$

(1.75)

These equations make it possible to find frequency of oscillation/vibrations $\omega$, of amplitude of voltages/stresses $U_1$ and $U_2$ on resonator gaps and phase of voltage/stress $\varphi$ on output gap (actually $\varphi$ is determined phase difference of voltages/stresses $U_2$ and $U_1$, equal to $\varphi + \pi/2$, since we assigned phase $U_1$, after accepting $\dot{U}_1 = -iU_1 = U_1 e^{-i\pi/2}$. It is not difficult to ascertain that during the identical tuning/adjusting of resonators $(\omega_{01} = \omega_{02} = \omega_0)$ the best conditions for generation take place at $\theta = 2\pi N$. In this case $\omega = \omega_0$, $\varphi = 0$. This mode/conditions corresponds to the center of the zone of generation [in reflex klystron analogous mode/conditions it occurs with $\theta = 2\pi(N+3/4)$].

We utilize equations (1.75) for determination of fluctuations of amplitude and frequency, called low-frequency noises of electronic flux. So, as in reflex klystron, the noises of electronic flux cause the fluctuations of the electronic conductivities of the high-frequency gaps of klystron and fluctuation of the time of flight of electrons in the space of drift. Assuming/setting

$$I = \bar{I} + \delta I(t), \quad g_{1,2} = \bar{g}_{1,2} + \delta g_{e\,1,2}(t),$$

$$\omega_{01,2} = \bar{\omega}_{0\,1,2} - \frac{\delta b_{e\,1,2}(t)}{2C_{1,2}}, \quad \theta = \bar{\theta} + \delta\theta(t),$$

we will search for the solutions in the form:

$$U_{1,2} = \bar{U}_{1,2} + \delta U_{1,2}(t), \quad \omega = \bar{\omega} + \delta\omega(t), \quad \varphi = \bar{\varphi} + \delta\varphi(t).$$

Since method of solution of this problem was in detail examined based on example of reflex klystron, omitting intermediate linings/calculations, let us give result of computations for case $\theta = 2\pi N$ (optimum transit angle):

$$\begin{aligned}
\frac{\delta U_2(t)}{\bar{U}_2} &= \frac{J_1(\overline{X})}{\overline{X} J_1'(\overline{X})} \left[ \frac{\delta I(t)}{\bar{I}} - \frac{\delta g_{e2}(t)}{\bar{g}_2} - \right.\\
&\qquad \left. - \frac{\overline{X} J_1'(\overline{X})}{J_1(\overline{X})} \frac{\delta g_{e1}(t)}{\bar{g}_1} \right], \\
\delta\omega(t) &= \frac{\bar{\omega}}{2(Q_1 + Q_2)} \left[ -\delta\theta(t) - \frac{\delta b_{e1}(t)}{\bar{g}_1} - \right.\\
&\qquad \left. - \frac{\delta b_{e2}(t)}{\bar{g}_2} \right].
\end{aligned} \qquad (1.76)$$

Page 68.

Let us note that during computation of fluctuations value $\sqrt{g_1 g_2}\, K_c$ was considered constant, since

$$K_c = \frac{M_c}{\sqrt{L_1 L_2}}\, Q_1 Q_2 \sim \frac{1}{\sqrt{g_1 g_2}}\ .$$

Let us compare formulas (1.76) with analogous formulas (1.39), obtained for reflex klystron. At the optimum transit angle ($\overline{\Delta \theta}=0$) of formula (1.39) they take the form:

$$\left.\begin{aligned}
\frac{\partial U(t)}{\overline{U}} &= \frac{J_1(\overline{X})}{\overline{X}\, J_2(\overline{X})}\left[\frac{\partial I(t)}{\overline{I}} - \frac{\partial g_e(t)}{\overline{g}}\right], \\
\delta \omega(t) &= \frac{\overline{\omega}}{2 Q_H}\left[-\delta \theta(t) - \frac{\partial b_e(t)}{\overline{g}}\right].
\end{aligned}\right\} \qquad (1.77)$$

Here $\partial g_e(t) = \partial g_e'(t) + \partial g_e''(t)$, $\partial b_e(t) = \Delta b_e'(t) + \Delta b_e''(t)$ fluctuation of electronic conductivities of gaps introduced with straight/direct and reverse transits. We see that the structure of formulas (1.76) and (1.77) is identical. If we compare klystrons with the identical average parameters and the same- type gaps, then it is possible to consider that the initial disturbances/perturbations (i.e. the fluctuation of electronic conductivities and transit angle) in both cases are close in the value. Then the difference in equations of the

fluctuations of frequency is caused only the fact that in formula (1.76) for $\delta\omega(t)$ (span klystron) the sum of the partial qualities of resonators figures. Since one of the resonators, not connected with the external load, can have high quality, under the stipulated conditions the level of the fluctuations of oscillator frequency on the span klystron is lower than in reflex klystron. Evaluations/estimates show that with the gaps with the grids it is possible to rely on the gain, which does not exceed 10 dB.

Formulas for fluctuations of amplitude are distinguished only by the fact that in span klystron effect of fluctuations of electronic conductivity of input gap is weakened/attenuated the more considerably, the nearer bunching parameter to optimum (from decrease of factor $\dfrac{\overline{X} J_1'(\overline{X})}{J_1(\overline{X})}$ ). For reflex klystron the electronic conductivities, introduced with the straight/direct and reverse transits of gap, enter into formula for the fluctuations of amplitude equally. However, this difference is unessential, so so the effect of the fluctuations of electronic conductivities on the fluctuation of amplitude is considerably weaker than the straight/direct effect of the fluctuations of current $\delta I(t)/\overline{I}$. Therefore during the identical mode/conditions and in the parameters of generators on span and reflex klystrons the levels of their amplitude noise must be close ones in the value.

It is interesting to note fluctuations of amplitudes of voltages on input and output gaps of generator on span klystron that they are

different.  Expression for the fluctuations of the amplitude of
voltage/stress on the input gap takes the form:

$$\frac{\delta U_1(t)}{\overline{U}_1} = \frac{\delta U_2(t)}{\overline{U}_2} - \frac{\delta g_{e1}(t)}{\overline{g}_1}.$$

Page 69.

This difference is virtually unessential in view of the fact that
value $\delta g_{e1}(t)/\overline{g}_1$ - is low in comparison with $\delta I(t)/\overline{I}$ and, consequently,
$\delta U_2(t)/\overline{U}_2 \approx \delta U_1(t)/\overline{U}_1$.


From entire that stated above it follows that in identical
mode/conditions, parameters and constructions/designs of gaps of
generators on span and reflex klystrons levels of mean squares of
their fluctuations of frequency are distinguished $\left(\frac{Q_H}{Q_1 + Q_2}\right)^2$ once, where
$Q_H$ - quality of resonator of reflex klystron, and $Q_1$ and $Q_2$ - partial
qualities of resonators of span klystron.  The levels of the
fluctuations of amplitude are virtually identical.


Let us pause now at fluctuations, excited by shf noises of
electronic flux.  So as in the case of reflex klystron, the action of
these noises can be reduced to slow modulation of amplitude and phase
of the fundamental harmonic of the current, induced in the gap of
output resonator, which makes it possible to use for calculating the
fluctuations of amplitude and frequency quasi-static method.  Omitting
description of calculations and amplitudes of voltage/stress on the
output gap of klystron at the optimum transit angle ($\overline{\theta} = 2\pi N$):

$$\frac{\delta U_2(t)}{\bar{U}_2} = \frac{B(t)}{2M\bar{I}\,\bar{X}\,J_2(\bar{X})},$$

$$\delta\omega(t) = \frac{\bar{\omega}}{2(Q_1+Q_2)}\,\frac{A(t)}{2M\bar{I}J_1(\bar{X})}.$$    (1.78)

Here A(t) and B(t) - slowly changing random functions, spectral densities of mean squares of which are determined by spectral densities of noise currents, induced in input and output gaps of klystron.  During the calculation of the noise current, induced in the output gap, just as in reflex klystron, one must take into account combination effects and action of the fluctuations of speed.

For comparison with reflex klystron we utilize expressions (1.58), after recording them for case of optimum transit angle [ $\bar{\theta}=2\pi N+3/4$ ]:

$$\frac{\delta U(t)}{\bar{U}} = \frac{b(t)}{2M\bar{I}\,\bar{X}\,J^2(\bar{X})},$$

$$\delta\omega(t) = -\frac{\omega}{2Q_{\text{н}}}\,\frac{a(t)}{2M\bar{I}J_1(\bar{X})}.$$    (1.79)

We see that structure of formulas (1.78) and (1.79) is identical. Let us assume that $\overline{A^2(t)}=\overline{a^2(t)}$ $\overline{B^2(t)}=b^2(t)$. Then the levels of the mean squares of the fluctuations of amplitude in generators of both types are identical, and the levels of the mean squares of the fluctuations of frequency are distinguished $\left(\frac{Q_{\text{н}}}{Q_1+Q_2}\right)^2$ once, i.e., the result of comparison the same as for the fluctuations, called by the low-frequency noises of electronic flux.

Both in reflecting and in span klystrons, order of magnitudes of
spectral densities of functions a(t), b(t), A(t), B(t), is determined
by level of spectral convective current density of ray/beam; on this
assumption about nearness of values $\overline{a^2(t)}$ and $\overline{A^2(t)}$, $\overline{b^2(t)}$ and $\overline{B^2(t)}$
is based.

Page 70.

Detailed examination shows that with the identical noises of
electronic flux and the optimum grouping these values in any case
remain within the limits of one order.

Thus, during identical mode/conditions, parameters and
constructions/designs of gaps generators on span and reflex klystrons
are characterized by adjacent levels of fluctuations.  This is correct
both with respect to the fluctuations, called the low-frequency, and
shf noise of electronic flux.

If we pose problem of obtaining lowest possible level of
fluctuations of frequency, then preference should be given to
generator on span klystron.  Matter in the fact that the most common
means of a decrease in the level of fluctuations of frequency without
the application of the external stabilizing systems is the decrease of
the perveance of electronic flux, in essence due to an increase in
accelerating voltage.  This is caused by the following:
    - with the decrease of perveance are reduced the values of
electronic conductivities and density of space charge of ray/beam,

which weakens/attenuates the effect of low-frequency noises during the fluctuation of frequency;

- with the sufficiently large accelerating potential is possible to use gridless gaps and to ensure better current flow. This reduces the noise level of current distribution and secondary emission. The elimination of Joule losses in the grids contributes to an increase in the quality of oscillatory system;

- level of shf noises of electronic flux also to be lowered, since with the small perveance to more easily avoid serious electron-optical defects with the formation of ray/beam and high level of surplus shf noises associating them.

It is natural that during use high-voltage feed it is expedient to attempt to combine low noise level with increased power of generator. In this respect span klystron has an advantage, possessing higher efficiency. Furthermore, principle of the device/equipment of span klystron excludes the possibility of the entry of the "mastered" electrons into the region near the cathode. In reflex klystron the part of the electrons returns to the cathode, and this can be the reason for an additional increase in the noise of cathode current.

At present lowest levels of fluctuations without application of supplementary stabilizing systems are obtained precisely in high-voltage generators on span klystrons with gridless gaps (see §5 Chapters 4). However, this way is not always acceptable, since most frequently simultaneously with low-level requirement of fluctuations

is advanced the series/row of others, that affect weight, size, retuning of generator, etc. In similar cases the selection of constructing/designing the generator is determined by entire complex of requirements and to frequently more reasonably give preference to simpler and more convenient in use reflex klystron, utilizing for noise reduction the external or conjugated/combined with it structurally stabilizing systems (see S4 Chapter 4).

4. Regular constituting in the noise spectra of klystron oscillators.

During study of noise spectra of klystron oscillators it is possible to reveal/detect narrow-band overshoots - regular components (Fig. 1.16). These overshoots are caused by the almost periodic (regular) processes, which lead to modulation of amplitude and frequency of klystron.

Page 71.

Regular components can appear in noise spectra under different mechanical influences on klystron: vibrations, impacts, acoustic effects. The nature of such regular components is connected with the mechanical oscillations of the separate parts of klystron, and we will call this form of regular components vibration regular components.

Regular components can also appear in noise spectra of klystrons and in the absence of mechanical effects. We will call such regular components static regular components.

4.1.  Vibration regular constituting.

The vibration of parts of klystron causes modulation of frequency
and amplitude of generatable oscillations.  Modulation of frequency
presents the greatest danger.  The maximum value of such a modulation
corresponds to the fundamental frequency of vibration effect; on its
higher harmonics modulation also is observed; however, it rapidly
weakens with an increase in the number of harmonic.  The usual
frequency band of the vibration effects during the use of klystrons in
the equipment, placed on the aircraft, ships, tractors, etc., ranges
from several hertz to several kilohertz, and accelerations can reach
10-15 g.  Upon the accelerations indicated the deviation of the
generatable frequency during the vibration even in most
vibration-proof reflex klystrons is 10-50 kHz, while the transit
klystrons have - several kilohertz.
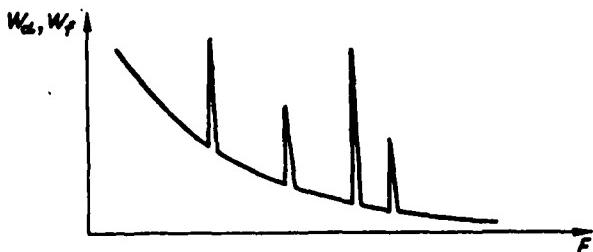
Fig. 1.16. Noise spectrum of klystron oscillator with regular components.

Page 72.

For klystrons, which work in centimeter and millimeter ranges, deviation of generatable frequency at fundamental vibration frequency, as a rule does not present essential danger, since it lies/rests beyond limits of low-frequency boundary of Doppler frequency band interesting. However, even the weakened deviation of frequency on the higher harmonics of vibration effect, which lie within the Doppler range, can energetically substantially exceed the power of frequency noises in the sufficiently narrow band of receiver.

If passband of receiver of system, in which is utilized klystron, is equal to $\Delta F$, and spectral density of mean square of random component of frequency noise $W_f$, then ratio of deviation of frequency, caused by regular effect, to effective deviation of frequency, determined by random effect, is equal

$$\delta f_{вибр} / \overline{W_f \Delta F}.$$

Let us examine characteristic relationships/ratios.  At the frequency F=5 kHz in reflex klystron with the usual noise level spectral density $W_f$ has value on the order of 1 Hz$^2$/Hz while $\delta f_{вибр}$ =10$^2$-10$^3$ Hz (at the fundamental frequency of vibration 1-2 kHz). Typical value of the band of the transmission of receiver $\Delta F$=500 Hz. then $\frac{\delta f_{вибр}}{\sqrt{W_f \Delta F}}$ =4.5=45, which corresponds to the excess of the regular component deviations frequency above the random on 13-33 dB.

If spectrum of vibration effect carries complicated character (for example, simultaneous vibration of klystron at many frequencies), then the caused by this effect large number of regular components at close frequencies can be revealed as lift in the level of fluctuations in individual sections of spectrum.

For decrease in level of such vibration of regular components to level of random noise it is necessary with the aid of damping is decreased value of vibration effect to 3-5 g, and in certain cases (on especially low noise levels) even to tenth and hundredths g, or to use special antihunting circuits of frequency of klystron.

However, under vibration influences with relatively small accelerations in noise frequency spectrum are observed separate intense regular components at frequencies, which are not harmonics of fundamental frequency of vibration effect.  The frequencies of such

vibration of regular components do not depend on the frequency of vibration effect and have for each sample/specimen of klystron the completely specific values.  This form of vibration in the regular components is connected with the mechanical resonance of the parts of klystron (microphonics), and their elimination is very complicated technical problem.

Page 73.

Therefore, without examining the general problems of the vibration resistance of klystrons, we in more detail will pause at microphonics.

Let us examine fundamental design concept of contemporary vibration-proof reflex klystron with system of connected resonators (Fig. 1.17 ).  The significant part of the parts has relatively simple form, and the resonance frequencies of the mechanical oscillations of such parts can be easily calculated by the known formulas of the drag theory of materials [104].
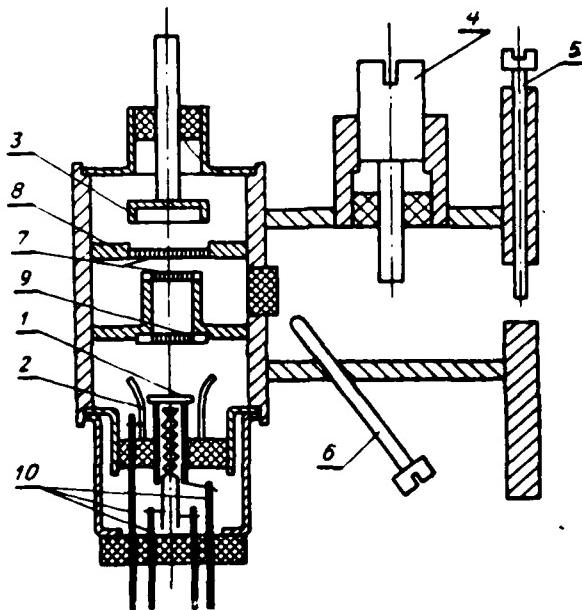
Fig. 1.17. Diagrammatic representation of construction/design of reflex klystron with connected resonators: 1 - cathode; 2 - focusing electrode; 3 - reflector; 4 - screw/propeller of retuning of frequency; 5 - screw/propeller of coupling adjustment with load; 6 - screw/propeller of coupling adjustment between resonators; 7 - grids, which form resonator gap; 8 - holder of grid - wall of resonator; 9 - accelerating grid; 10 - conclusions/outputs.

Page 74.

For example, the resonance frequency of the fundamental form of the transverse oscillations of the focusing electrode, screw/propeller of coupling adjustment between the resonators, the screw/propeller of the coupling adjustment of klystron with the load can be evaluated according to formula for the beam/gully of round cross section [105]:

$$f_{pe_3} = 1{,}245 \frac{a^2 d}{l^2} \sqrt{\frac{E}{\gamma}} , \qquad (1.80)$$

where $f_{pe_3}$ - the resonance frequency of the fundamental form of transverse oscillations, Hz; $l$ - length of the free part of part (length of beam/gully), cm; $\gamma$ - density of material kg/cm³; E - modulus of elasticity of material, kg/cm²; $\sqrt{E/\rho}$ - value, proportional to the speed of propagation of sound in the material; $\alpha$ - root of the equation of frequencies, depending on form and rigidity of anchorage and presence of other masses on the part.

Calculations show that values of resonance frequencies for parts enumerated above, and also for cathode and conclusions/outputs, with real sizes/dimensions and materials range from several kilohertz to 100 kHz, i.e., directly in Doppler frequency band. However, the amplitudes of the oscillations of parts are usually negligible, and the sensitivity of the output parameters of klystrons to the lateral motions of the parts in question is relatively small. Therefore in the contemporary klystrons different adjusting screws, parts of electron guns or assemblies of reflector, as a rule are not the direct source of noticeable vibration regular components. These parts can be the reason for the appearance of vibration regular components in the noise spectrum either during the unsuccessful construction/design of the corresponding node or during the technological disturbances/breakdowns of the process of assembly (poor welding or soldering, the gap of parts, etc.).

On other matter concerning oscillations of grids and walls of resonator of klystron proceeds. A change in the value of working resonator gap due to the oscillations of grids or end walls of resonator produces abrupt changes in the frequency of the generated by klystron. However, in a number of cases to increase to the necessary values the rigidity of grids and walls is in principle impossible due to the requirements, which escape/ensue from the very designation/purpose of the elements of construction/design in question. Let us pause at these considerations in more detail. A change in the resonance frequency of the toroidal oscillatory circuit of the klystron, in which working gap is overlapped by grids, depending on the value of the working gap d is determined by the expression:

$$\frac{\partial f_0}{\partial d} \approx \frac{f_0}{2d} \frac{4d + \pi a}{\pi a + 4d \ln h/d}, \qquad (1.81)$$

where h, 2a - height/altitude of resonator and the diameter of its central flange respectively.

Page 75.

Taking into account real ratios of dimensions of resonators, it is possible for tentative calculations to accept value $\partial f_0/\partial d = (6-8) \cdot 10^{-4} f_0$ MHz/$\mu$m. Thus, in the X—band a change of the resonance frequency of duct/contour is approximately 7 MHz on 1 $\mu$m of a change in the value of working gap. Since frequency modulation on the order of hundreds hertz already is completely inadmissible the appearance intense vibration regular constituting, then it becomes

clear, that the virtually negligible oscillations of grids or end walls of resonator with the sonic or supersonic frequencies can seriously affect the normal work of equipment.  In this connection of special interest are the self-resonant frequencies of the parts of resonator, with which the amplitude of oscillations is maximum and becomes inadmissible already under the extremely small external influences.

Let us examine dependence of resonance frequencies of oscillations of grids on their geometric dimensions as example.  For the analysis let us select the copper net of honeycomb construction/design, which extensively is used in contemporary low-voltage klystrons [101].  If we present the natural mechanical oscillations of grid as the oscillations of elastic plates, pinched on the edges, then its resonance frequency can be determined from following expressions [29]:

$$\omega^2_{pes} = \frac{k^4_\phi D}{\rho \, t_c a^4_c} , \qquad (1.82)$$

$$D = \frac{E \, t^3_c}{12(1 - \nu^2)} . \qquad (1.83)$$

In these expressions $\omega_{pes}$ - resonance frequency in angular units; $k_\phi$ - factor of form of oscillations (for dominant mode of oscillations tabular value $k_\phi \approx 3.2$); D - rigidity; $t_c$ - thickness of grid; $a_c$ - radius of free (not soldered through) part of grid; $\nu$ Poisson ratio (for copper $\nu = 0.35$); $\rho = \gamma/g$ - reduced density of material; $\gamma$ - density

(for copper $\gamma=8.6\cdot10^{-3}$ kg/cm$^3$); g - acceleration of gravity.

If we consider loss of rigidity of grid due to openings/apertures in it in comparison with monolithic plate, after introducing coefficient $\xi_c$ (empirical values $\xi_c$ for usually utilized sizes/dimensions of honeycomb grids they lie/rest within limits 0.4=0.6), then from expressions (1.82) and (1.83) we will obtain formula for calculating resonance frequency of oscillations of grid

$$f_{pes} = \frac{k_\phi^2\, t_c}{2\pi\, a_\xi^2} \sqrt{\frac{E\,\xi_c\, g}{\gamma\, 12\,(1-\nu^2)}}. \qquad (1.84)$$

Page 76.

According to results of calculation it is constructed with Fig. 1.18, in which are also plotted/applied experimental points, obtained during analysis of vibration regular components of klystrons with different grids.  The completely satisfactory coincidence of calculated and experimental data indicates the possibility of using formula (1.84) for the evaluation/estimate of one or the other methods of fight with vibration regular components, caused by the oscillations of grids.

As example let us attempt to solve problem of eliminating vibration regular components, connected with resonance mechanical oscillations of grids, in operating range of Doppler frequencies during design of klystron of three-centimeter wavelength range.  Mesh sizes at such klystrons usually lie/rest in limits    $a$ =2-3.5 mm,

$t_c$ =0.2-0.6 mm and, consequently   $f_{pes}$ =15- 120 kHz.

Let us accept for operating range of Doppler frequencies of station  $F_z$ =5-200 kHz (in number of cases this range it can be considerably wider than selected).

For displacing resonance frequency of mechanical oscillations of grids beyond limits of operating range of Doppler frequencies should be either decreased rigidity of grids, on the basis of condition $f_{pes} < F_{\text{д мин}}$, or it is essential to increase rigidity for guaranteeing condition $f_{pes} > F_{\text{д макс}}$. The first condition is satisfied, as it follows from Fig. 1.19, with $t_c < 0.1$ mm or with $a_c > 6.5$ mm if $t_c = 0.2$ mm.
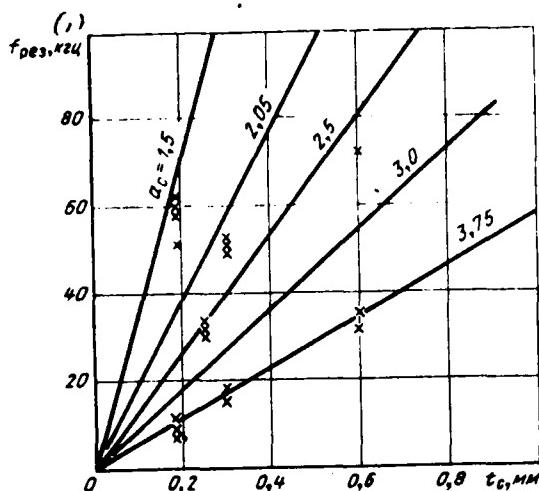
Fig. 1.18.  Dependence of resonance frequency of natural mechanical oscillations of copper honeycomb grid on its geometric dimensions (radius  $a_c$  and thickness  $t_c$ ).

Key:  (1).  kHz.

Page 77.

Increase in diameter of grids to necessary value is technically impossible, since it is limited to sizes/dimensions of resonator of klystron and, in particular, with radius of central flange of the resonator, which in X-band does not exceed 3 mm.  Decrease in the rigidity of grid due to the decrease of its thickness to also prove to be it is not possible to solve problem.

Without dwelling in detail at technological difficulties, connected with use of fine screens, let us note that in this case operating characteristics of klystron substantially deteriorate:  is

reduced vibration stability, decreases ultimate capacity, scattered by grids, reliability and life respectively is reduced.  However, the fundamental factor, hindering a decrease in the rigidity of grids, is an increase in the intensity of the highest types of mechanical oscillations.  Thus, for example, with the rigidity of grid, which corresponds to the resonance frequency of 2-4 kHz, the intensity of the third form of oscillations proves to be sufficient for the onset of corresponding vibration regular components.

Since for third form of oscillations $k_\phi = 6.3$, then frequencies of these components are equal to 8-15 kHz, i.e., they lie/rest within limits of operating range of Doppler frequencies.

Thus, elimination of vibration regular components in frequency noise spectrum of klystron by decrease in rigidity of grids in principle is impossible.  In connection with this let us examine another path - an increase in the rigidity of grids, i.e., the guarantee of condition $f_{pe3} > F_{1 \text{ макс}}$.

From expression (1.84) it follows that for obtaining resonance frequencies of grids, greater than 200 kHz, radii of grids must be less than 1 mm with thicknesses of grids 0.2-0.3 mm or thickness of grids it must exceed 1-2 mm with radii of 2-3 mm respectively.

In principle creation of klystron with grids with thickness on the order 1 mm or with radius of about 1 mm is possible; however, here

there are sufficiently serious technical limitations.  With radii of electronic flux, smaller 1.5-2 mm, to avoid the inadmissible increase in the current density, removed from the cathode, appears the need of using the electron-optical systems with the considerable compression, i.e., the use of electronic fluxes with the large angles of convergence.  In this case usually increases current interception by grids, which leads to reduction efficiency in the klystron, deterioration in the series/row of the operating parameters and among other things to an increase in the noises of klystron.  The use of grids of the increased thickness leads to the analogous consequences due to a sharp increase in current interception.  For span type grid klystrons, which have not less than four grids and using the electrostatic focusing of electronic flux, the maximum thickness of grid on current interception conditions is approximately 0.5 mm.

In reflex klystrons grids with thickness of more than 0.6-0.7 mm also usually are not used.

From aforesaid it is possible to draw following important conclusion:  vibration regular components, caused by oscillations of grids, to completely remove in entire Doppler frequency band cannot, although, raising rigidity of grids in reasonable limits, it is possible to weaken/attenuate this phenomenon.

All these reasonings, which relate to oscillations of grids, are valid also for oscillations of end walls of resonators.

Amplitudes of oscillations of grids or resonators, sufficient for appearance vibration regular components, are extremely small; therefore with coincidence of frequency of external effect with resonance frequency of natural mechanical oscillations of these parts vibration regular components can appear already with negligible amount of exciting force.

Page 78.

In this case become dangerous high-frequency vibration effects at frequencies into tens of kilohertz with the intensity of the order of the tenth and hundredths g. The same relates also to the acoustic effects on the low-noise klystron.

Application of damping is one of fundamental paths of fight with microphonics. During the use of conventional means of damping equipment the vibrational accelerations relatively easily decrease at the high frequencies. In connection with this it can seem that the problem of the suppression of resonance oscillations of grids and walls of the resonators of klystrons is solved comparatively simply, since frequencies of such usually compose tens of kilohertz. However, the practice of operation and checking of klystrons under the conditions of vibration effects shows that even at the frequencies of vibration 100-200 Hz and with the virtually purely sinusoidal form of vibration oscillations in the noise spectrum of klystron can appear intense vibration regular components at frequencies, which correspond

to the mechanical resonance of grids or walls of resonator.

Investigations showed that by driver of parts at self-resonant frequencies under vibration influences, whose frequency to 2-2.5 orders lower than resonance, is collision excitation. If during the vibration of klystron in the equipment appears friction or rapping against each other of the badly/poorly attached parts of mounting (wires, screens/shields, washers, etc.), then the appearing wide frequency spectrum of collision excitation, which seizes the self-resonant frequencies of the mechanical oscillations of grids or walls of resonator, can cause the appearance of corresponding vibration regular components. The aforesaid equally relates also to friction of the badly/poorly attached parts of klystron itself (heater in the cathode, insulators, fine-adjustment screws/propellers, etc.).

4.2.  Static regular constituting.

Appearance of static regular components in noises spectrum of klystron can be caused by both the external reasons (pulsations of feeding voltages/stresses, radio engineering focusings/inductions) and by internal reasons, determined by complicated physical processes in klystrons themselves. On the external reasons we shall not dwell.

Page 79.

It is completely clear, for example that if in the spectrum of the pulsation of any of the supplies of power of klystron is a narrow-band

overshoot at the specific frequency, which lies at the Doppler
operational frequencies band of the equipment, then in the noise
spectrum of klystron at the appropriate frequency will appear regular
component.  It is easy to rate/estimate the value of such regular
component, knowing the sensitivity of the frequency generated by
klystron to a change in the supply voltage.

We analyze approximations (1.11)- ( 1.13), connecting change
generatable frequencies and by change in voltages of supply of
klystron.  The sensitivity of generated frequency to the
voltage/stress on the resonator for reflex klystron, as it follows
from expression (1.12), can be sharply reduced when $V_R \approx V_0$. The
corresponding relationships/ratios of the geometric dimensions of
klystron, necessary during construction, are represented in work [30].
The comparison of expressions (1.11) with (1.13) shows that the
sensitivity of the generatable frequency to the feeding
voltages/stresses in span klystron is 5-10 times lower than in
reflecting during the comparable operating modes, since the quality of
the resonator system of the span klystron respectively is 5-10 times
higher than reflecting.  However, from the point of view the effects
of the instability of the feeding voltages/stresses on the appearance
of static regular component of requirement for the power supplies for
the reflecting and span klystron prove to be equivalent.  Matter in
the fact that with an increase in the quality of resonator system is
reduced not only the value of frequency modulation and, consequently,
the absolute value of static regular component, but will be reduced

and the level of frequency noise.  Therefore the excess of static

regular component above the noise level remains constant/invariable.

From expressions (1.11)- (1.13) it also follows that with the decrease

of the number of the zone of generation the sensitivity of the

generatable frequency to the feeding voltages/stresses is reduced.

Fight with radio engineering focusings/inductions during

operation of coherent equipment is very complicated and important

problem.  Both the focusings/inductions along ether/ester and the

focusings/inductions along the network/grid of feed can be developed

in the form of static regular components in the noise spectrum of

klystron; however, in connection with the fact that a similar form of

static regular components is not connected directly with the

construction/design or the modes/conditions of the work of klystron

oscillator, we will not stop on the particulars of the suppression of

focusings/inductions and their effect on the distortion of noise

characteristics.  Let us pass to the examination of the internal

reasons for the appearance of static regular components, i.e., such

reasons, which are determined by physical processes in klystron

oscillator.

Page 80.

The known at present internal reasons for appearance of klystrons

static regular component in noise spectrum one way or another are

connected with processes, which take place in ion-electron plasma,

which is formed in region of electronic flux.

Oscillations of ion-electron plasma, modulating in frequency and amplitude of oscillation of klystron, lead to appearance single static regular components or whole series of such components in noise spectra.  It is clear that one of the paths of fight with static regular components of this origin is sharp lowering in the pressure of residual gases in the working instrument, i.e., the guarantee of an ultrahigh vacuum during entire service life of klystron.  It was established, for example, that in the span klystrons, in which at a common for vacuum-tube instruments pressure of residual gases of order $10^{-6}$-$10^{-7}$ mm Hg were noted these intense static regular components they disappeared with decompression to $10^{-8}$- $10^{-9}$ mm Hg [31].

Fig. 1.19 gives typical noise spectra of span klystron at different pressures of residual gases.

From aforesaid it would be possible to make conclusion that since static regular components are caused by oscillations of ions, and decrease in final pressure of residual gases in klystron is capable of tearing away such oscillations, there is no need to in detail examine complicated physical processes, which determine development of one or the other modes of ionic vibrations, and it is necessary only with methods of contemporary technology to ensure required vacuum in working klystrons. However, this conclusion/output would be inaccurate on a number of circumstances.
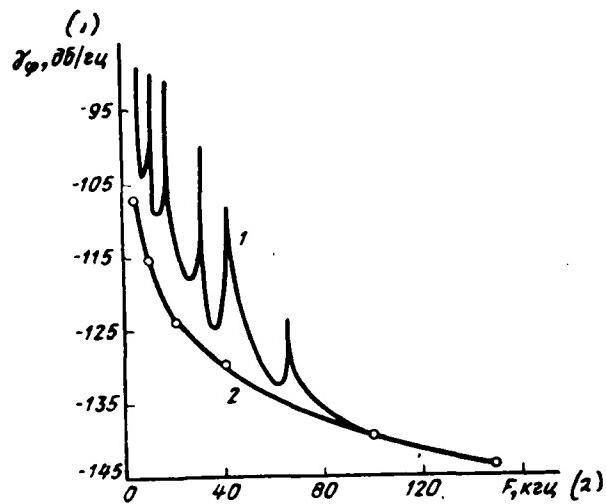
Fig. 1.19. Frequency noises of span generator klystron at pressure of residual gases $10^{-6}-10^{-7}$ (1) and $10^{-8}-10^{-9}$ (2) mm Hg.

Key: (1). dB/Hz. (2). kHz.

Page 81.

First, obtaining and maintenance of required ultrahigh vacuum in klystrons during operation in heavy temperature conditions during entire guaranteed service life is very complicated technical problem. Even with of the solution of this problem in the principle are always possible short-term vacuum deteriorations with the continuous operation of klystron due to random voltage surges of feed, technological divergences in modes of cleaning/decontamination of assemblies and parts of klystron and exhaust schedules, due to the concealed/latent material defects and other difficultly considered and badly/poorly controlled factors. To reveal/detect previously the

possibility of similar pressure shocks in the working klystron is virtually impossible.  For the majority of usual of electric vacuum and among other things shf instruments a change of the pressure in the limits of $10^{-1}$-$10^{-4}$ mm $Hg$          does not cause the disturbance/breakdown of efficiency of instrument.  However, for the low-noise klystrons the changes in the pressure indicated are dangerous, since they can cause the appearance of static regular components in the spectra fluctuations and give pentrite themselves and to the disturbance/breakdown of efficiency of equipment.

Secondly, even under ideal conditions for evacuation of residual gases in working klystron are always vapors of metals.  The pressure of the vapors of barium, for example, during the use of oxide cathodes and especially high-temperature impregnated cathodes reaches the value of $10^{-1}$-$10^{-4}$ mm Hg [32].  The ionized vapors can also cause different modes of the plasma vibrations, which are accompanied by the appearance of static regular components.

Therefore solution of problem by guarantee of stable fine vacuum in process of operating klystrons although is very important, it is insufficient for reliable work of low-noise klystron oscillators.  It is necessary already during construction of klystrons to attempt to remove or at least to maximally restrict very possibility of the development of those modes of the ionic vibrations, which are capable of causing appearance in the noise spectrum of static regular components.

Page 82.

Let us examine different modes of ionic plasma vibrations.  In this case us they will interest the relatively low-frequency vibration modes, capable of causing spurious modulation in the Doppler frequency band.

Are at present known following low-frequency ionic oscillations: relaxation type oscillation, oscillation at ionic plasma frequency, oscillation of ions in region of minimum of potential near the cathode, oscillations, connected with formation/education in plasma of electrostatic acoustic waves.

Relaxation type oscillations.  Fig. 1.20 schematically shows electron-optical systems and distribution of electric potential along the axis of reflecting and span klystrons.  In the space between accelerating grid and first resonator grid and in the middle part of the span tube the electrons move in the region, where external electric field virtually is absent.  In this case under the effect of negative space charge of electronic flux potential in the axis of klystron noticeably is reduced and appears the "potential pit" (region of the minimum of potential), which is the reason for the onset of relaxation oscillations.

In working klystron as a result of collisions of electrons with molecules of residual gases positive ions are formed.  If the grids of klystron are sufficiently dense, then space boundary by them is trap

for the positive ions and, since the process of ionization occurs continuously, then ions are accumulated in the trap.  In proportion to the accumulation of positive ions negative space charge of electronic flux is compensated and potential well depth decreases.  The same process occurs also in the span tube without the grids, if it has sufficiently large length in comparison with the inside diameter, since in this case the leak/leakage of ions to the side of cathode is hindered/hampered.  Now let us turn to physics of relaxation oscillations.

Depending on depth of potential Java can occur two forms of relaxation oscillations, whose mechanisms differ from each other.

For simplicity of reasonings we will consider that The klystron has ideal grids, i.e., grid such dense that they completely shield electric field, and at the same time such transparent for electronic flux that value of current interception can be disregarded/neglected.

Page 83.

In this case in the absence of potential well or with its relatively small depth (curves I and II on Fig.  1.20a) entire electronic flux, which left the cathode and which passed accelerating grid $C_1$, will achieve working resonator gap and it will interact with shf field of resonator, determining the output parameters of klystron - amplitude and the frequency of the generatable.

If ionic space-charge neutralization is absent and potential well depth is maximum (curve III), i.e., potential is reduced to zero and so-called virtual cathode is formed, then special current distribution between electrodes of klystron appears.
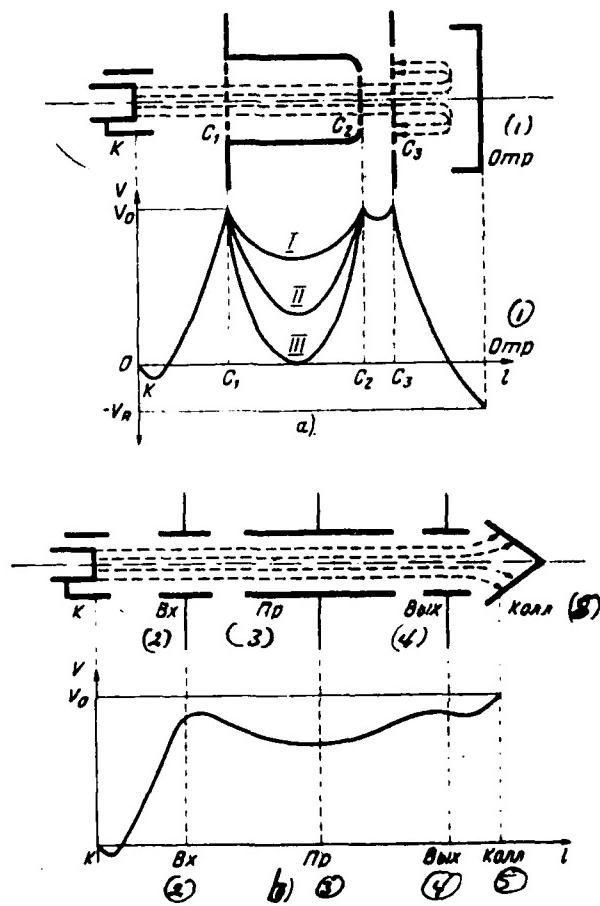
Fig. 1.20. Diagrammatic representation of electron-optical systems and potential distribution along axis of reflecting (a) and span (b) klystrons: K - cathode; $C_1$ - accelerating grid; $C_2$, $C_3$ - resonator grid;       - reflector;                         input span and outtakes; - collector/receptacle.

Key: (1). Reflector. (2). Input. (3). Span. (4). Output. (5). Collector.

Page 84.

The region of virtual cathode will be able to overcome only the part

of the electrons, whose speed will prove to be somewhat larger than average/mean.  Taking into account the known distribution law on initial velocities of electrons, it is possible to consider that half of the electrons, which will achieve working resonator gap, will be able to pass approximately the region of virtual cathode.  Remaining electrons will return back into the region between the cathode and accelerating grid.  In this case the output parameters of klystron will be others in comparison with the mode/conditions of the absence of virtual cathode, since they will be determined by doubly smaller operating current.  Furthermore, it is important that in this mode/conditions space charge in cathode due to the returning electrons will increase and will occur the supplementary decrease of operating current.  Thus, are possible two modes of operation of klystron, determined by the presence or the absence of virtual cathode, and to these two modes/conditions will correspond to two values of the output parameters.

When in klystron sufficient quantity of positive ions is present, both modes/conditions are established/installed alternately with specific periodicity, which causes modulation of output parameters. This occurs as follows.

Upon inclusion of accelerating voltage at zero time ions are absent and is established/installed mode/conditions of virtual cathode.  The process of ionization gradually increases a number of ions and, since in the region of klystron in question external

electric field virtually is absent, positive ions are accumulated in the region of the minimum of potential. Because of ionic space-charge neutralization of electronic flux the potential well depth decreases also at some moment of the time, when potential becomes more than zero, the mode of operation of klystron sharply is changed. In this case due to the decrease of a quantity of electrons in the region between the cathode and accelerating grid common cathode current grows/rises, which causes a new increase in the potential well depth. Then potential well depth again decreases also at some moment of time begins maximum ionic compensation, the field, which contributed ion concentration in the region of the minimum of potential, disappears and ions gradually are scattered.

In proportion to scattering ions potential well again appears. In connection with the relatively low speeds of ions, determined by their large mass, occurs an increase in the potential well depth up to the formation of virtual cathode again abruptly they are changed mode/conditions and the output parameters of klystron.

Page 85.

Further process is repeated in the form of periodic oscillations. With the typical form of such oscillations (Fig. 1.21) highest harmonic components are very intense and therefore in the noise spectrum of klystrons whole series of static regular components with the multiple frequencies can be observed.

Frequency, as it follows from that outlined above, depends on time of reaching/achievement of ionic compensation, i.e., from quantity of positive ions, formed in region of ion trap per unit time. Therefore frequency is the greater, is the greater the number of molecules or the greater the pressure of residual gases in klystron. At real pressures of residual gases of the frequency of dominant mode of oscillations usually they lie/rest at the region from hundred hertz to several ten kilohertz and taking into account the appearance of highest harmonic components encompass virtually entire operating range of Doppler frequencies.

Establishment of any intermediate equilibrium of work prevents, first, inertia of ions and, secondly, the fact that condition for formation of the virtual cathode and condition for its disappearance are different, i.e., are different critical values of density of electronic flux. In more detail with the physico mathematical treatment of the described phenomena the reader can be introduced in work [33]. Let us point out only to the connection/communication of the geometric dimensions of the ion trap with the distance from the cathode to accelerating grid. These connection/communication is determined by the existence of the critical density of space charge of electronic flux, at which in the region of the ion trap can be formed virtual cathode.

In work [33] it is shown that in idealized electron-/electronic-optical system of span klystron (grid ideal, wall effect of span tube

on potential distribution in electronic flux it is not considered)
virtual cathode cannot arise, if length of tube is lower than doubled
distance from cathode to accelerating grid.
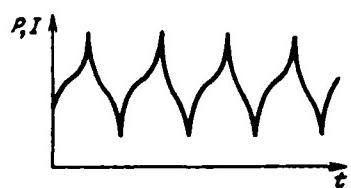
Fig. 1.21.  Typical picture of oscillations of relaxation form in klystrons.

Page 86.

Respectively for reflex klystron, where the density of space charge increases due to the electrons, which enter the region of the ion trap from the direction of reflector, virtual cathode cannot arise if the length of the ion trap (distance between grids $C_1$ and $C_2$ in Fig. 1.20) will be less than 1.7 of distance between the cathode and grid $C_1$.

in real constructions/designs, where grids intercept part of electronic flux, into effect of side walls of cylindrical pipe, which forms ion trap, sag/sagging potential decreases on axis of electronic flux depending on relation of diameters of tube and flow, given higher than relationship/ratio will be others.  Nevertheless, these idealized relationships/ratios can be recommended for the calculations of the geometric dimensions of klystrons, since they are maximum for the existence of virtual cathode.  The effect of supplementary factors in the real constructions/designs will create only the structural/design reserves, which guarantee the absence of virtual cathode, and consequently, and the absence of the described above mode of

relaxation vibrations under any working conditions of klystron. However, the mechanism of relaxation oscillations examined not the only possible, and the elimination of virtual cathode in a number of cases does not guarantee the suppression of static regular components.

In klystrons, in which there are no conditions for formation of virtual cathode, but there is sufficiently large sag/sagging of potential due to effect of negative space charge of electronic flux and has the capability of leak/leakage of ions from ion trap to side of cathode, relaxation oscillations of another form can appear. So as with the first form of relaxation oscillations, after the inclusion/connection of accelerating voltage in proportion to an increase in the quantity of positive ions decreases potential well depth. In this case the electron-optical stream conditions of electrons change and the output parameters of klystron respectively change.

After reaching/achievement of complete ionic space-charge neutralization of electronic flux unstable equilibrium appears. The appearance of any "excess" positive ion causes the onset of the force of pushing apart, which to lead to the bias/displacement of ions along the axis of flow to the side of cathode. In this case through the opening/aperture the leak/leakage of ions to the cathode increases, and this creates the supplementary electric field, "which extracts" ions from the trap. There occurs a rapid release of trap from the positive ions, but in this case potential well, where ions, again

begin to be accumulated/stored again appears, and processes are repeated. Storage time determines the oscillatory period, since it to 1-2 orders usually exceeds the time of the release of trap from the ions.

Page 87.

Described form of relaxation oscillations was investigated in work [34] on carcinotrons, but results of this work were applicable for analysis of mechanism of relaxation oscillations in klystrons. Frequency $(f_{pea})$ can be calculated according to the formula

$$f_{pea} = \frac{p \, \sigma_j(V_0) \, \sqrt{2e \, V_0/m}}{\rho_j/\rho_e} \, . \tag{1.85}$$

where p - pressure in klystron, mm Hg; $\sigma_j(V_0)$ - specific ionization (number of ions, produced by one electron at the length of 1 cm at a pressure 1 mm Hg); $\rho_j/\rho_e$ - ratio of the density of ionic charge and density of electronic charge (with $P \geq 10^{-4}$ mm $Hg$ $\rho_j/\rho_e \approx 1$).

With the aid of formula (1.85) it is not difficult to show that frequencies of dominant mode of oscillations during usual modes of operation of klystrons lie/rest within limits of 5- 100 kHz and taking into consideration of intense highest harmonic components they encompass entire Doppler range. For the suppression of similar oscillations besides an improvement in the vacuum there is actually one path - complete elimination of the ion traps in the constructions/designs of klystrons for the avoidance of the appearance

of potential wells.

Oscillations of ions in region of minimum of potential near the cathode.  In S 2 it was indicated that with the passage of the positive ions through the region of the minimum of potential near the cathode the fluctuations of cathode current, which call an increase in the noises of klystron, appear.  In this case were examined the ions, formed as a result of the ionization of residual gases and which move in I will move cathode with the relatively high speeds.  However, in klystrons, where thermionic cathodes are utilized, into the region of the minimum of potential near the cathode enter also the ions, emitted by cathode.

Such ions, possessing low speeds, can be seized in region of minimum of potential and complete about this region of oscillation, causing appropriate periodic modulation of electronic flux.  The predicted mechanism of the excitation of oscillations is reduced to the following.

Ion flow of barium, which leave cathode, falls into region of minimum of potential, where there is ac field.  This field causes modulation of ions on the speeds and, consequently, modulation of the ionic flow with respect to density. The modulated on the density ion flow forces to fluctuate in the potential well depth (in the near-cathode region of the minimum of potential) how is realized the feedback, which supports oscillations.

Page 88.

Study of similar oscillations is given to [40], where is used following expression for calculating frequency:

$$f_{j\kappa} = \frac{\pi^{3/4}}{2^{1/4}} \frac{\eta_1^{1/2}}{\xi_- + \xi_+} \frac{m^{1/4} e^{1/2}}{m_j^{1/2} (kT_\kappa)^{1/4}} J, \qquad (1.86)$$

where $T_\kappa$ - temperature of cathode; $m_j$ - mass of ion; J - density of electronic current; k - Boltzmann constant; m, e - mass and electron charge; $\eta$, $\xi_-$, $\xi_+$ - dimensionless parameters, tabulated by Langmuir.

Rough estimate of frequency of barium ions gives value of approximately 5 MHz.

Thus, it is possible to consider that static regular components, which can be caused in noise spectrum of klystron by described mode of ionic vibrations, will lie/rest beyond limits of Doppler frequency band.

Oscillations at ionic plasma frequency. It is known that in the electronic fluxes neutralized by ions the sustained oscillations, caused by the oscillations of the ions of plasma, can appear. The theory of such oscillations was developed by Langmuir and Tonks [35]. Similar oscillations can appear also in the electronic shf instruments. To the studies of the physical mechanism of ionic oscillations in the confined plasma, threaded by the flow of fast electrons, is dedicated the series/row of works [36-39, 41], but far

from all sides of the occurring processes are sufficiently studied,
there are many contradictory and debatable conclusions/outputs and
assumptions.

Reference [36] is one of the most successive works in the
field of ionic oscillations in low-pressure confined plasma
pierced by an electron beam, where the expression for frequency
of cross plasma oscillations $f_{jp}$ is given.

With cylindrical form of plasma column frequency $f_{jp}$ is
determined as follows:

$$f_{Ip} \approx 0,48 \cdot 10^6 \left( \frac{J}{M_j V \sqrt{V_0}} \right)^{1\,2} . \qquad (1.87)$$

where j - density of electronic current, A/m$^2$; $M_j$ - molecular weight
of ions; $V_0$ - voltage/stress of electronic flux, V.

For klystrons of centimeter wavelength range operating
voltages/stresses are 250-4000 V, and currents of cathode 30-60 mA
with diameters of electronic flux 2—4 mm.  Therefore frequencies of
ionic plasma in the klystrons in accordance with expression (1.87)
must lie/rest within the limits of 0.5-3 MHz for the usual fundamental
residual gases $N_2$ and CO $(M_j=28)$ and 2-11 MHz for $H_2(M_j=2)$.

Page 89.

Corresponding static regular components can, consequently, be
developed in the noise spectra of klystrons only in high-frequency

polishing Doppler frequency band.

However, in plasma can exist electrostatic waves, whose frequencies are lower than ionic plasma frequency. Wave in this case is similar to acoustic wave in the gas, when speed does not depend on density. Therefore similar waves were called "electrostatic acoustic waves". The theoretical and experimental studies of such waves are presented, for example, in works [42, 43].

Under specific conditions, when intense interaction of electrostatic wave with flow of slow (for example, secondary) electrons occurs, longitudinal or radial sustained oscillations can appear. Similar oscillations were observed both in the span klystrons [44] and in the reflecting.

A characteristic difference in oscillations of a radial type is the fact that the highest frequencies are not multiples of the lower critical frequency, but rather that their ratio corresponds approximately to the ratio of the roots of the Bessel functions.

Work [44] resulting expressions for determination of limiting frequencies of transverse oscillations for cylindrical column of plasma.

In the absence of azimuthal dependence

$$J_0(\beta_c b) = J_1(\beta_c b)\beta_c b \ln c/b. \qquad (1.88)$$

In presence of azimuthal dependence

$$J_1(\beta_c b) = J_0(\beta_c b)\frac{\beta_c b}{2}(1 - c^2/b^2),\qquad (1.89)$$

where $\beta_c = \left(\dfrac{\omega_{jp}^2 m_j}{\gamma k T_e}\right)^{1/2}\left(\dfrac{\omega_{jp}^2}{\omega_c^2} - 1\right)^{-1/2};$

b - radius of plasma column; c - radius of tube of drift; $J_0$, $J_1$ - function of Bessel of first order; $\omega_{jp}$ - angular ionic plasma frequency; $m_j$ - mass of ion; $T_e$ - electron temperature of plasma; k - Boltzmann constant; $\gamma$ - coefficient of adiabatic compression (according to data [42, 42] $\gamma=2-3$); $\omega_c$ - angular limiting frequency.

When $\omega_c^2 \ll \omega_{jp}^2$

$$\beta_c \approx \omega_c\left(\frac{m_j}{\gamma k T_e}\right)^{1/2}.$$

From expression (1.89), in particular, it follows that with complete filling of tube of drift with plasma, when c/b=1, frequencies relate between themselves as roots of function of Bessel $J_1$. With other values of c/b of relationship/ratio are more complicated.

Table 3 gives calculated and experimental relationships/ratios of frequencies for span klystron with tube of drift with diameter of 1.93 mm according to data of work [44] and analogous relationships/ratios for reflex klystron with diameter of tube of 4 mm. In Table $\omega_n/\omega_1$ - the ratio of the critical frequency of the n-type of oscillations/vibrations to lowest critical frequency (n=1).

In Fig. 1.22. calculated curves, carried out according to expression (1.89), are given.

Data, given in Table 3, show that experimental relationships/ratios of frequencies satisfactorily coincide with calculated. However, as a rule absolute values of calculated frequencies, which correspond to real residual gases in the klystrons $(M_j = 2 - 28)$, it is considerably higher than the experimental values of frequencies. For explaining this nonconformity in work [44] assumed that fundamental ion component is created by barium $(M_j = 137)$, which evaporates from the cathode, but sufficient data, that confirm this hypothesis, no.

Is possible that decrease in frequency connected with high-constituent nature of real plasma in klystrons, but at present detailed examinations of this plasma present very great difficulties.

Table 3.   Relationships/ratios of the highest types of frequencies.

| (1) Тип клистрона и режим работы | (2) Номер колебания, n | (3) Частота колебаний, кгц (4) Эксперимент | ωп/ωi (4) Эксперимент | (5) Теория |
|---|---|---|---|---|
| (6) Пролетный $V_0 - 9,5$ кв, (7) $I_к = 79$ ма, (8) $b/c = 1$ | 1 2 3 4 | 254 465 665 825 | 1,0 1,83 2,62 3,25 | 1,0 1,83 2,65 3,48 |
| (6) Пролетный $V_0 = 4,8$ кв, (7) $I_к = 30$ ма (8) $b/c = 0,65$ | 1 2 3 4 5 | 155 320 459 723 872 | 1,0 2,06 2,96 4,66 5,63 | 1,0 2,02 3,11 4,18 6,0 |
| (9) Отражательный $V_0 = 300$ в, (10) $I_к = 34$ ма (8) $b/c = 0,7$ | 1 2 3 4 5 | 46,5 93 150 198 244 | 1,0 2,0 3,23 4,26 5,25 | 1,0 2,0 3,12 4,13 5,35 |

Key:  (1).  Type of klystron and the operating mode.  (2). The number of oscillations, n.  (3).  Frequency kHz.  (4).  Experiment.  (5). Theory.  (6).  Span.  (7).  kV.  (8).  mA.  (9).  Reflecting.  (10). V.

Page 91.

The examinations of simpler two-component plasma [45] indicate the possibility of both the decrease and increasing the frequency depending on the combination of ion concentrations with different masses.  Complexity and insufficient study of oscillating processes in the real multicomponent plasma impede at present fight with corresponding static regular components. constituting.  Nevertheless, will examine some paths of fight with the ionic oscillations/vibrations, based on the experimental data and on the overall physical representations about the mechanism of ionic oscillations/vibrations.

Without dwelling on need for improvement in vacuum (which can, generally speaking, prove to be ineffective, if is accurate hypothesis about determining role of the vapors of barium), let us point out to need for stability of partial pressures of residual gases in klystron. The redistribution of ion concentrations with different masses in the process of the prolonged operation of klystron can cause ionic oscillations/vibrations due to a change in attenuation length of Landau.
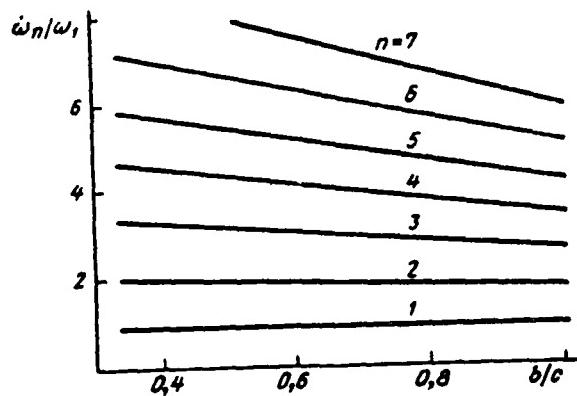
Fig. 1.22. Dependence of computed values of relative frequencies of radial in plasma $\omega_n/\omega_1$ from ratio of radius of plasma column to radius of drift tube b/c.

Page 92.

In connection with the fact that mechanism of energy transfer to oscillating plasma is connected, apparently, with presence of slow secondary electrons [36, 42, 44], should be excluded or sharply restricted possibility of entry of secondary electrons from collector/receptacle or walls of span tube into region of plasma column '.

FOOTNOTE ' Generally speaking, the oscillations of secondary electrons can be the reason for the appearance of klystrons static regular component in the noise spectra, but the frequencies of such components are assumed to be relatively high - order of tens of megahertz. Furthermore, secondary electrons, falling into the region of electronic flux, contribute to the formation/education of "potential

traps," which favorably affects the onset of relaxation type
oscillations.  ENDFOOTNOTE.

Positively must pronounce decrease of ionic concentration due to
the leak/leakage of ions from the region of the tube of drift.  This
consideration is confirmed experimentally in work [44], where with an
increase in the negative bias/displacement on the collector/receptacle
it was possible to tear away ionic oscillations/vibrations.  The
physical explanation of disruption/separation connected with the fact
that with the decrease of ion concentrations is reduced ionic plasma
frequency $\omega_{jp}$ and, when $\omega_{jp}^2$ it becomes close to $\omega_c^2$,
oscillations/vibrations are broken away.

Page 93.

Chapter 2.


Parameters, which characterize noisiness of generators, and the

methods of their measurement.

1.  Parameters, which characterize noisiness of generators.

1.1.  Oscillation spectrum with those fluctuating by amplitude and

frequency.  *S*pectral line width.


Whatever physical processes, which reveal stability of

oscillations/vibrations of generator, result of their action can be

represented in the form of oscillation/vibration those fluctuating by

amplitude and frequency:

$$U(t) = \overline{U}\left[1 + \alpha(t)\right] \cos\left[\overline{\omega} t + \int v(t)\, dt + \varphi_0\right], \qquad (2.1)$$

where $\alpha(t) = \delta U(t)/\overline{U}$ – relative fluctuation of amplitude; $v(t) = 2\pi \delta f(t)$ –

fluctuation of angular frequency; $\overline{U}$ and $\overline{\omega}$-average/mean values of

amplitude and frequency respectively, and $\varphi_0$ – constant phase,

determined by initial conditions.  Subsequently we will count $\varphi_0 = 0$.


Since change in phase accompanies any change in frequency,

moreover $v(t) = d\varphi(t)/dt$, it is possible to record (2.1) f to this form:

$$U(t) = \overline{U}\left[1 + \alpha(t)\right] \cos\left[\overline{\omega} t + \varphi(t)\right]. \qquad (2.2)$$

In steady-state mode/conditions amplitude and frequency of

generator are statistically stationary processes, if their calling

noises also are statistically stationary.  This means that the

amplitude and frequency have completely specific average/mean values, and their fluctuations are virtually limited in the value. The fluctuations of phase behave otherwise. The random disturbances of phase are not restored, and in the course of time the divergence of phase can become large, in spite of the smallness of the fluctuations of frequency. Analysis shows that random component of the phase of generator changes under the noise effect similarly to the coordinate of particle during the Brownian (thermal) motion.

Page 94.

Let us examine spectrum of fluctuating oscillation U(t). Obviously, its form is determined by the character of the spectra of the fluctuations of frequency and amplitude. The task of determining the mathematical connection/communication between the energy oscillation spectrum and the energy spectra of its fluctuations in the general case is complicated. Therefore we will be restricted only to simple considerations and evaluations/estimates, sufficient for understanding of the essence of matter; the reader will find the detailed presentation of a question in [46].

If we deal concerning purely harmonic process of $U(t) = \bar{U}\cos\bar{\omega}t$, then its spectrum is infinitesimally narrow line (Fig. 2.1). Let us examine how the spectrum changes, if occur only the fluctuations of amplitude, i.e.

$$U(t) = \bar{U}[1 + \alpha(t)] \cos\bar{\omega}t. \qquad (2.3)$$

Let us assume that spectral density of mean square of

fluctuations of amplitude $W_a(F)$ is known (Fig. 2.2.).  In order to clearly present the connection/communication between the oscillation spectra U(t) and fluctuations of amplitude α(t), let us replace noise effect with the action of the sum of harmonic oscillations.  Let us break frequency interval, on which assigned spectral density $W_a(F)$, on N of equal narrow sections let us compare to noise in each of these sections the harmonic oscillation, whose amplitude it is selected from the condition of the equality to power of harmonic oscillation during the period and the power of noise [1];

$$a_n^2/2 = W_a(F_n) \Delta F. \qquad (2.4)$$

FOOTNOTE [1].  More precisely saying, from the condition of the equality of the mean squares of harmonic oscillation and noise α(t). ENDFOOTNOTE.

Obviously, relationship/ratio $a_n^2/2\Delta F$ reflects the course of energy spectrum $W_a(F)$ at discrete/digital points $F=F_n$. This means that the noise effect and its replacing harmonic oscillations they are equivalent in the energy sense.
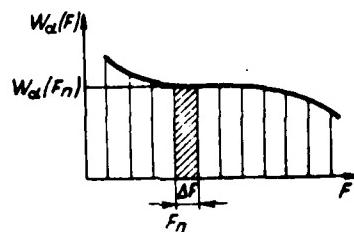
Fig. 2.1.                          Fig.   2.2.

Fig. 2.1.   Energy spectrum of harmonic oscillation.

Fig. 2.2.   Energy spectrum of fluctuations of amplitude.

Page 95.

Taking into account aforesaid it is possible to record (2.3) ·in following form:

$$U(t) = \overline{U} \left[ 1 + \sum_{n-1}^{n-N} a_n \cos \Omega_n t \right] \cos \overline{\omega} t =$$

$$= \overline{U} \cos \overline{\omega} t + \sum_{n-1}^{n-N} \frac{\overline{U} a_n}{2} \cos (\overline{\omega} + \Omega_n) t +$$

$$+ \sum_{n-1}^{n-N} \frac{\overline{U} a_n}{2} \cos (\overline{\omega} - \Omega_n) t, \qquad (2.5)$$

where $\Omega_n = 2 \pi F_n$.

It is hence evident that oscillation spectrum U(t) consists of carrier with amplitude $\overline{U}$ and symmetrically arranged/located relative to it lateral modulation frequencies with amplitudes of $\frac{U a_n}{2}$. Since the level of the amplitude noise of real generators is very small, then $a_n \ll 1$ and fundamental vibrational energy is concentrated in the infinitesimally narrow frequency range at the frequency of carrier. The oscillations of the side frequencies of the amplitude modulation

form the pedestal, on the form repeating to the right and to the left
of the modulating function α(t) carrying the spectrum. Carrier output
is equal to $P_0=\bar{U}^2/2$, while the power of lateral, arranged/located from
it at a distance $\pm F_n$ in the bands with a width of $\Delta F$,

$$[P_6(F_n)]_{2\Delta F}=\frac{\bar{U}^2 a_n^2}{8}+\frac{\bar{U}^2 a_n^2}{8}-\frac{\bar{U}^2 a_n^2}{4}-\frac{\bar{U}^2 W_a(F_n)\Delta F}{2}.$$

Hence we obtain

$$\frac{[P_6(F_n)]_{2\Delta F}}{P_0}=W_a(F_n)\Delta F. \qquad (2.6)$$

In accordance with (2.6) ratio of power of transverse
oscillations of amplitude modulation in band Δf=1 Hz to carrier output
oscillation is numerically equal to spectral density of fluctuations
of amplitude.

Page 96.

Strict examination [46] leads to the same results. Thus, if is
assigned the energy spectrum of the fluctuations of amplitude $W_a(F)$
(Fig. 2.2), then energy oscillation spectrum U(t) with the fluctuating
amplitude consists of the sum of discrete/digital line on the
frequency of carrier and pedestal, repeating on the form to the right
and to the left of carrying line spectrum $W_a(F)$ (Fig. 2.3). Retains
force and relationship/ratio (2.6):

$$\frac{[P_6(F)]_{2\Delta F}}{P_0}=W_a(F)\Delta F. \qquad (2.7)$$

In self- excited oscillators order of width of spectrum of
fluctuations of amplitude is determined by passband of oscillatory
duct/contour (resonator). We saw this based on the example of reflex
klystron. Thus, the width of the pedestal of the oscillation spectrum

of autogenerater is of the order the passband of oscillatory circuit.

Let us examine now oscillations, modulated only in frequency:

$$U(t) = \overline{U} \cos \left[\overline{\omega} t + \int v(t)\,dt\right] = \overline{U} \cos \left[\overline{\omega} t + \varphi(t)\right]. \qquad (2.8)$$

In order to explain, as oscillation spectrum U(t) in this case appears, let us recall properties of oscillation, frequency-modulated by harmonic tone.   This oscillation can be recorded in the following form:

$$U(t) = \overline{U} \cos \left[\overline{\omega} t + \int \varkappa \cos \Omega t\,dt\right] =$$

$$= \overline{U} \cos \left[\overline{\omega} t + \frac{\varkappa}{\Omega} \sin \Omega t\right].$$

$$(2.9)$$

where $\Omega$ - angular modulation frequency; $\varkappa$ - deviation of frequency, and $\varkappa/\Omega$ - index of modulation (deviation in phase).   From the theory of frequency modulation it follows that the oscillation of form (2.9) can be represented by the sum of spectral components:

$$U(t) = \overline{U} \sum_{s=-\infty}^{s=+\infty} J_s \left(\frac{\varkappa}{\Omega}\right) \cos (\overline{\omega} + s\Omega) t, \qquad (2.10)$$

where $J_s \left(\frac{\varkappa}{\Omega}\right)$ - function of Bessel of the s order.

Expression (2.10) shows that even with simple sinusoidal modulation spectrum of frequency modulated oscillation contains infinite number of components, from those standing from each other to value $\Omega$.
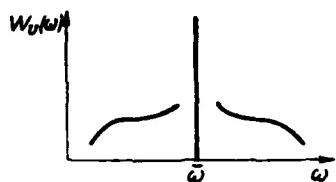
Fig. 2.3.  Energy oscillation spectrum with fluctuating amplitude.

Page 97.

With the amplitude modulation by the simple tone are only three
spectral components:  carrying and two lateral, distant behind it up
to the frequency distance $\pm\Omega$.  Carrier level depends on the depth of
modulation; with the smallness of the latter the energy of the
amplitude modulated oscillation virtually completely is concentrated
on frequency of carrier.  In the case of frequency modulation the low
value of the deviation of frequency $\kappa$ does not mean that the
amplitudes of transverse oscillations are compulsorily small.
Everything depends on the frequency at which modulation occurs.  With
the given $\kappa$ always will be located sufficiently low values $\Omega$, with
which the index of modulation $\kappa/\Omega$ will become comparable with one and
even it is substantially more than one.  The properties of the Bessel
functions are such, that with the value of the argument of order the
numbers of function, value $J_s\left(\dfrac{\kappa}{\Omega}\right)$ prove to be comparable with $J_0\left(\dfrac{\kappa}{\Omega}\right)$.
This means that in spite of low value $\kappa$, at the sufficiently low
modulation frequency vibrational energy is distributed along the
spectrum, but it is not concentrated in the oscillation of the carrier
frequency as with modulation of amplitude.

Example of spectrum of frequency modulated oscillation with value

of index of modulation $\kappa/\Omega=10$ is shown in Fig. 2.4.  In spite of the

fact that the spectrum contains an infinite number of components [see

formula (2.10)], from Fig. 2.4 it is evident that the amplitudes of

transverse oscillations sharply decrease with $|s|>\kappa/\Omega$.  This is a

common property of the Bessel functions and it is correct with any

value of the index of modulation $\kappa/\Omega$.  Therefore it is possible to

speak about the completely specific width of the spectrum, if we

understand it as the frequency band, in which is concentrated

fundamental energy of the frequency modulated oscillation.
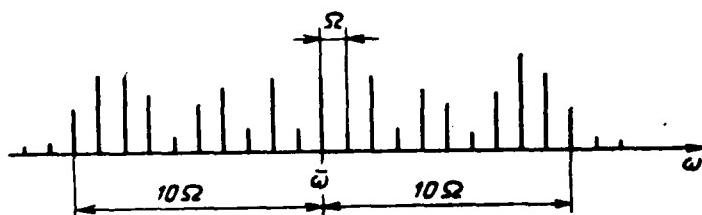
Fig. 2.4. Oscillation spectrum, frequency-modulated by harmonic tone of frequency $\Omega$ with index of modulation, equal to 10.

Page 98.

Taking into account that the frequencies of transverse oscillations are located from each other on value $\Omega$, it is possible to propose the following evaluation/estimate for the width of the spectrum:

$$\Delta\omega \approx 2\Omega s_{\text{макс}},\qquad (2.11)$$

where $s_{\text{макс}} = \varkappa\Omega$ - number of the transverse oscillation, with excess of which sharply decrease the amplitudes of side components. Then formula (2.11) can be rewritten in the following form:

$$\Delta\omega \approx 2\varkappa.\qquad (2.12)$$

With constant/invariable deviation of frequency ($\varkappa$=const) width of spectrum is obtained identical for any modulation frequency $\Omega$. With the decrease $\Omega$ the spectrum is filled more densely; however, in view of the decrease of distance between spectral components they all are localized in limits of one and the same frequency interval $\Delta\omega \approx 2\varkappa$.

Joint action of many modulating oscillations considerably complicates picture; oscillation spectra are not simply superimposed, but appear new components due to crossed effects.

Entire above- mentioned related to case of modulation of frequency by harmonic oscillations. The qualitative aspect of phenomena will be preserved also in the case of modulation of noise frequency, since its action, at least in the root-mean-square sense, always can be replaced with the action of a large number of harmonic oscillations. A strict analysis confirms this [46]. Actually, with random modulation of frequency the vibrational energy is distributed along the spectrum; energy oscillation spectrum $W_U(\bar{f} - F)$ - the spectral density of the mean square of oscillation U(t) - is eroded and is converted from the discrete/digital line into the duct/contour of the final width with the maximum at the medium frequency of oscillation $\bar{f}$ (Fig. 2.5). The width of spectral duct/contour is defined as the frequency band, the prisoner of honey by the points, at which $W_U(\bar{f} - F)$ is equal to half from maximum value $W_U(\bar{f})$. Both the form and the width of spectral duct/contour depend on character the energy spectrum of the fluctuations of angular frequency $W_\nu(F) = (2\pi)^2 W_f(F)$ [let us recall that $\nu = 2\pi \delta f(t)$].

Page 99.

If value $W_\nu(F)$ is low and weakly it changes at the low frequencies (spectrum "low" and wide - Fig. 2.6), then the width of spectral duct/contour is designed from formula [46]

$$\Delta F_e = \frac{W_\nu(0)}{8} . \qquad (2.13)$$

FOOTNOTE [1]. This formula differs from that given in [46] in terms of constant coefficient, since here and into [46] are utilized different determinations of the energy spectrum:  in [46] the spectral density is referred to the interval of angular frequency $\Delta\Omega$, and here - to $\Delta F = \Delta\Omega/2\pi$ (see appendix 2).  ENDFOOTNOTE.

We see that $\Delta F$, - depends only on value of spectral density of fluctuations of frequency near F=0.  In light of the explanations, given above for the model with harmonic modulation of frequency, this must not cause the surprise:  line broadening is obliged to the action only of those spectral components of the fluctuations of frequency, for which the index of modulation is great.  With the low value of the level of the fluctuations of frequency the large index of modulation is obtained only at very low frequencies, i.e., with F≈0.  Since we examine the action of the fluctuations of frequency with the spectrum now, by those by weakly changing in the region of the low values F (Fig. 2.6), where $W$, $(F)$≈const, then level $W$, in this region can be sufficiently accurately characterized with its value with F=0 that also is utilized in formula (2.13).

Thus, formula (2.13) makes it possible to calculate line broadening in such a case, when spectrum of fluctuations of frequency at sufficiently low frequencies is close to uniform.  The spectral duct/contour of the oscillation, formed by the action of such fluctuations, is called natural; respectively and the width of duct/contour is called natural.  More frequently they speak about the natural spectral line width, but not duct/contour.
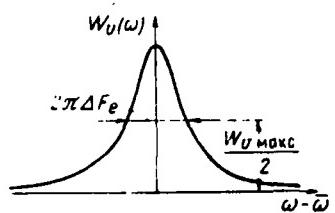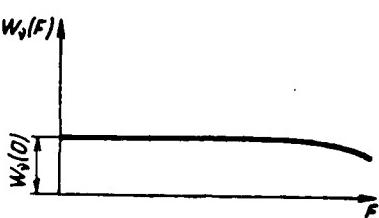
Fig. 2.5.                              Fig.   2.6.

Fig.  2.5.  Energy oscillation spectrum with fluctuating frequency (duct/contour of "spectral line").

Fig. 2.6.  "**W**ide" spectrum of fluctuations of frequency.

Page 100.

Although this terminology is not too successful (line does not have width), it solidly was affirmed in the literature.  It is possible to meet other names of the natural width of the line:  resonance, Lorentz.

Obviously, formula (2.13) is unsuitable for computing broadening of spectral line, caused by flicker effect, since in this case form of energy spectrum of fluctuations of frequency does not correspond to prerequisites/premises, accepted in conclusion/output (2.13): spectral density of component of fluctuations of oscillator frequency, caused by flicker effect, substantially grows/rises to low frequencies (Fig. 2.7).  In this case the width of spectral duct/contour is designed from following formula [46]:

$$\Delta F_{\tau} = \frac{1}{\sqrt{2\pi}} \sqrt{\int_{F_{\text{мин}}}^{F_{\text{макс}}} W_{\cdot}(F)\,dF}, \qquad (2.14)$$

where $F_{\text{МНН}}$ and $F_{\text{МНКС}}$ - band edge of frequencies, in limits of which the system, which uses a generator, reacts during the fluctuation of its frequency.  the spectral line width, caused by the action of the component of the fluctuations of the frequency, whose spectral density substantially grows/rises to the low frequencies, is called technical, Doppler or Gaussian.

In contrast to natural spectral line width, technical is determined not only by level of spectral density of fluctuations of frequency, but also by band, in which is developed action of fluctuations.  Thus, the technical width of line is not the absolute characteristic of generator, since it depends also on the conditions, under which it is recorded.  Value $\Delta F_{\text{т}}$ depends mainly on $F_{\text{МНН}}$, since $W_{\text{v}}(F)$ increases to the low frequencies.  However, with the nearness of the law of change $W_{\text{v}}(F)$ to $F^{-1}$ dependence $\Delta F_{\text{т}}$ on $F_{\text{МНН}}$ proves to be weak.  Let us examine an example.

Let $W_{\text{v}}(F) = AF^{-1,1}$. For simplicity let us accept $F_{\text{МНКС}} = \infty$, then

$$\Delta F_{\text{т}} = \frac{1}{\sqrt{2\pi}} \sqrt{\int_{F_{\text{МНН}}}^{\infty} AF^{-1,1}\, dF} = \sqrt{\frac{A}{0,2\pi}}\, F_{\text{МНН}}^{-0,05}.$$

hence follows that with change $F_{\text{МНН}}$ $10^3$ times $\Delta F_{\text{т}}$ it is changed only 1.4 times.  This makes it possible to judge an order of magnitude $\Delta F_{\text{т}}$ over a wide range of change $F_{\text{МНН}}$ by the value, determined in one of the points of range.

Page 101.

Let us give example of calculation of spectral line width according to results of measuring energy spectrum of fluctuations of frequency of reflex klystron.  Fig. 2.8 shows the spectrum of the fluctuations of frequency, obtained from the experiment.  To frequency $F \approx 10^4$ Hz the course of spectral density is determined by flicker effect, with $F > 10^4$ Hz - by noises with the uniform spectrum.  Is obvious, is possible to represent $W_f(F)$ by the sum:

$$W_f(F) = |W_f(F)|_{\phi\lambda} + (W_f)_{\text{равн}}.$$

The first of these components must produce the technical broadening of spectral line, and the second - natural.

In accordance with formula (2.13) for determining natural component of line width it is necessary to know level $(W_f)_{\text{равн}}$ near F=0. Direct measurement $(W_f)_{\text{равн}}$ with $F \approx 0$ is impossible, first of all, due to the flicker effect masking actions.  Therefore it is necessary to extrapolate value $W_f(F)$. obtained at the high frequencies, where the action of flicker effect weakens in a sufficient measure to the zero frequency.  Fulfilling this operation/process, we find

$$W_v(0) = (2\pi)^2 (W_f)_{\text{равн}} = (2\pi)^2 |W_f(F)|_{F > 10^4 \text{ зц}} \approx 0,4 \text{ rad}^2/\text{sek}.$$

Then, after substituting value $W_v(0)$ in (2.13), we will obtain $\Delta F_e = 0,05$ Hz.

For determining technical component of spectral line widths we extrapolate course $|W_f(F)|_{\phi\lambda}$ into region of high frequencies and integrate (numerically) $|W_f(F)|_{\phi\lambda} = (2\pi)^2 |W_f(F)|_{\phi\lambda}$ in limits $F_{\text{мин}} = 10$ Hz, $F_{\text{макс}} = 2 \cdot 10^5$ Hz.  As a result we find

$$\int_{F_{\text{мин}}}^{F_{\text{макс}}} W_{\text{ч}}(F)\, dF \approx 10^{9} \ \text{rad}^{2}/\text{s}.$$

In accordance with (2.14) we obtain $\Delta F_{\text{т}} = 12{,}5$ Hz.
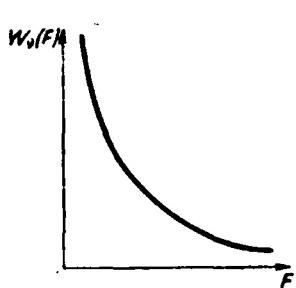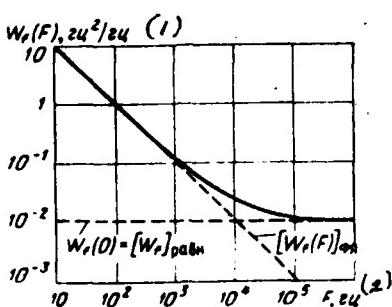
Fig. 2.7.                              Fig. 2.8.

Fig. 2.7. "narrow" spectrum of fluctuations of frequency, caused by flicker effect.

Fig. 2.8. Energy spectrum of fluctuations of frequency of reflex klystron on logarithmic scale (to calculation of components of spectral line width).

Key: (1). Hz²/Hz. (2). Hz.

Page 102.

Thus, technical component of spectral line width considerably exceeds natural. Since the spectrum of the fluctuations of frequency, depicted in Fig. 2.8 and used for the calculation, is typical for reflex klystrons of the short-wave part of the range of microwaves, one should consider that the flicker effect is the fundamental reason for the broadening of the spectral line of such klystrons.

Given example shows that width of the spectral line is very small - order ten hertz. Specifically, in this frequency range fundamental vibrational energy is concentrated. However, hence it does not follow that spectral components of the fluctuations of the oscillation of

generator, which lie far beyond the limits of spectral line width, are harmless (see Chapter 3). Therefore the knowledge of the course of the spectral densities of fluctuations over a wide range of frequencies is necessary not only for determining the spectral line width of generator. In most the frequency band of the fluctuations of being practical interest, begins far beyond the limits of the spectral width of line (Fig. 2.9).

Let us examine oscillation spectrum with fluctuating frequency now precisely for these frequencies (wings of spectral line). Let us enter so as in the case of oscillation with the fluctuating amplitude, after replacing noise effect with the action of the sum of the harmonic oscillations, whose amplitudes $\varkappa_n$ are selected so that the mean square of the fluctuations of angular frequency in this region of the spectrum with the width $\Delta F$ (Fig. 2.10) would be equal to the average/mean within the period square of the depicting harmonic function:

$$\frac{x_n^2}{2} = W_\bullet(F_n)\Delta F.$$

(2.15)
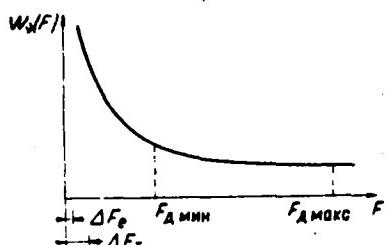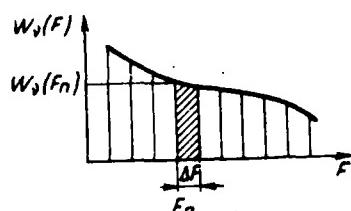
Fig. 2.9.                                      Fig. 2.10.

Fig. 2.9. Typical relationship/ratio of width of range of Doppler frequencies and technical and natural spectral line width.

Fig. 2.10. Section of energy spectrum of fluctuations of frequency, which determines wings of spectral line.

Page 103.

Then

$$U(t) = \overline{U} \cos \left[ \overline{\omega} t + \int \sum_{n=1}^{n=N} x_n \cos \Omega_n t \, dt \right] =$$

$$= \overline{U} \cos \left[ \overline{\omega} t + \sum_{n=1}^{n=N} \frac{x_n}{\Omega_n} \sin \Omega_n t \right].$$

Let us represent here $\sum_{n=1}^{n=N} \frac{x_n}{\Omega_n} \sin \Omega_n t$ as follows:

$$\sum_{n=1}^{n=N} \frac{x_n}{\Omega_n} \sin \Omega_n t = \psi_k(t) + \sum_{n=k}^{n=N} \frac{x_n}{\Omega_n} \sin \Omega_n t, \qquad (2.16)$$

where k - such number, with which

$$\sum_{n=k}^{n=N} \frac{x_n}{\Omega_n} \sin \Omega_n t \ll 1.$$

Obviously, frequency $\Omega_k$ lies/rests considerably higher than

cut-off frequency of spectral line, since indices of modulation $x_n / \Omega_n$ with n>k must be much less than one (inequality $\sum\limits_{n-k}^{n-N} \frac{x_n}{\Omega_n} \sin \Omega_n t \ll 1$  must be fulfilled at all moments of time).

Page 104.

Taking into account (2.16) U(t) it is possible to convert thus:

$$U(t) = \overline{U} \cos \left[ \overline{\omega} t + \psi_k(t) + \sum_{n-k}^{n-N} \frac{x_n}{\Omega_n} \sin \Omega_n t \right] =$$

$$= \overline{U} \cos [\overline{\omega} t + \psi_k(t)] \cos \left[ \sum_{n-k}^{n-N} \frac{x_n}{\Omega_n} \sin \Omega_n t \right] -$$

$$- \overline{U} \sin [\overline{\omega} t + \psi_k(t)] \sin \left[ \sum_{n-k}^{n-N} \frac{x_n}{\Omega_n} \sin \Omega_n t \right] \approx$$

$$\approx \overline{U} \cos [\overline{\omega} t + \psi_k(t)] - \overline{U} \sin [\overline{\omega} t + \psi_k(t)] \sum_{n-k}^{n-N} \frac{x_n}{\Omega_n} \sin \Omega_n t =$$

$$= \overline{U} \cos [\overline{\omega} t + \psi_k(t)] + \sum_{n-k}^{n-N} \frac{\overline{U} x_n}{2 \Omega_n} \cos [(\overline{\omega} + \Omega_n) t + \psi_k(t)] -$$

$$- \sum_{n-k}^{n-N} \frac{\overline{U} x_n}{2 \Omega_n} \cos [(\overline{\omega} - \Omega_n) t + \psi_k(t)]. \qquad (2.17)$$

This expression resembles spectrum, obtained for amplitude-modulated oscillation (2.5). Difference consists only of the fact that the phase of transverse oscillations of lower frequencies was turned on $180°$, and also in the fact that "carrying" and the transverse oscillations are additionally frequency-modulated (phase) by function $\psi_k(t)$. Let us note that function $\psi_k(t)$ - is slow,

since

$$\psi_k(t) = \sum_{n=1}^{n-k} \frac{x_n}{\Omega_n} \sin \Omega_n t, \text{ a } \Omega_n \ll \bar\omega, \bar\omega + \Omega_n, \bar\omega - \Omega_n.$$

Since all $x_n/\Omega_n$ in (2.17) is much less than 1, almost entire/all power of oscillation U(t) is contained in that slowly modulated "carrier," i.e., in limits of spectral line width.  On (2.17) this power (with an accuracy to constant factor) is equal to $P_0 = \bar{U}^2/2$ [1].

FOOTNOTE [1].  In actuality $\bar{U}^2/2$ - complete average/mean power of the frequency modulated oscillation U(t), including power of all lateral. From (2.17) it follows that $\bar{U}^2/2$ - only power of "carrier"; however, this conclusion/output - consequence of the approximations/approaches, made during conclusion/output (2.17).  ENDFOOTNOTE.

The power of lateral, arranged/located up to distances $\pm F_n = \pm \Omega_n/2\pi$ from the carrier, in the bands with a width of $\Delta F$ is equal to

$$[P_6(F_n)]_{2\Delta F} = \frac{\bar{U}^2 x_n^2}{8\Omega_n^2} + \frac{\bar{U}^2 x_n^2}{8\Omega_n^2} = \frac{\bar{U}^2 x_n^2}{4\Omega_n^2} = \frac{\bar{U}^2 W_v(F_n)\Delta F}{2\Omega_n^2}.$$

Hence follows that

$$\frac{[P_6(F_n)]_{2\Delta F}}{P_0} = \frac{W_v(F_n)\Delta F}{\Omega_n^2} = \frac{W_f(F_n)\Delta F}{F_n^2}. \qquad (2.18)$$

Page 105.

Since deviation of phase $\varphi_n$ and deviation of frequency $x_n$ are connected with relationship/ratio $\varphi_n = x_n/\Omega_n$, the relation $\frac{W_v(F_n)}{\Omega_n^2} = \frac{W_f(F_n)}{F_n^2}$ makes sense of spectral density of mean square of

fluctuations of phase [1].

FOOTNOTE [1]. The phase of the oscillation of any self-excited oscillator is statistically transient. Nevertheless, sufficiently rapid changes in the phase can be approximately considered stationary in the interval of the time, limited by the smallness of a change in the average/mean value of phase. In our model the transient properties of the phase of oscillation are hidden in function $\psi_k(t)$, and the fluctuations of phase at frequencies, which considerably exceed spectral line width, are considered stationary that it makes it possible to speak about their energy spectrum as independent of the time parameter. ENDFOOTNOTE.

This makes it possible to rewrite (2.18) as follows:

$$\frac{[P_6(F_n)]_{2\Delta F}}{P_0} = \frac{W_J(F_n)\Delta F}{F_n^2} = W_\varphi(F_n)\Delta F,$$

where $W_\varphi(F_n)\dfrac{W_J(F_n)}{F_n^2}$ - the spectral density of the fluctuations of phase.

Passing to continuous change in frequency, we can rewrite latter/last formula, after dropping/omitting index "n":

$$\frac{[P_6(F)]_{2\Delta F}}{P_0} = \frac{W_J(F)\Delta F}{F^2} = W_\varphi(F)\Delta F. \qquad (2.19)$$

On (2.19) the ratio of the power of side in the band frequencies, equal to 1 Hz ($\Delta f = 1$ Hz), to the average/mean power of oscillation it is numerically equal to the spectral density of the fluctuations of phase. Obviously, the power of one lateral, arranged/located at a

distance of F from the medium frequency of oscillation, it is possible to record thus:

$$[P_\delta(F)]_{\Delta F} = P_0 \frac{W_\varphi(F)}{2} .$$

At conclusion of present section briefly let us pause at combined action of fluctuations of frequency and amplitude. If the fluctuations of frequency and amplitude are not correlated, then the power of lateral, the frequencies caused by fluctuations and amplitudes, simply store/add up. The components of the spectral density of the fluctuating voltage/stress for this case are shown on Fig. 2.11.

Let us note that contribution of fluctuations of amplitude in the range of Doppler frequencies, as a rule is small.

Page 106.

Thus, the typical value of the spectral density of the fluctuations of amplitude at the frequency F=200 kHz composes $10^{-16}$ 1/Hz; if at the same frequency $W_f = 10^{-2}$ Hz$^2$/Hz, then

$$W_\varphi = \frac{W_f}{F^2} = \frac{10^{-2}}{4 \cdot 10^{10}} = 2,5 \cdot 10^{-13} \ 1/Hz,$$

consequently,

$$\frac{[W_U]_a}{[W_U]_f} = \frac{10^{-16}}{2,5 \cdot 10^{-13}} = 4 \cdot 10^{-4}.$$

At the low frequencies of fluctuations the difference is still more. If the fluctuations of frequency and amplitude are correlated, then the form of spectral line can be distorted, the fixture of asymmetric.

The order of spectral line width in this case is retained.

1.2.  The mean squares of the fluctuations of amplitude and frequency.

During analysis of noisiness of generators in Chapter 1 we characterized with their spectral densities of fluctuations of amplitude and frequency.  These parameters sufficiently fully reflect the effect of the instability of generator of the properties of one or the other systems, in which it is utilized.
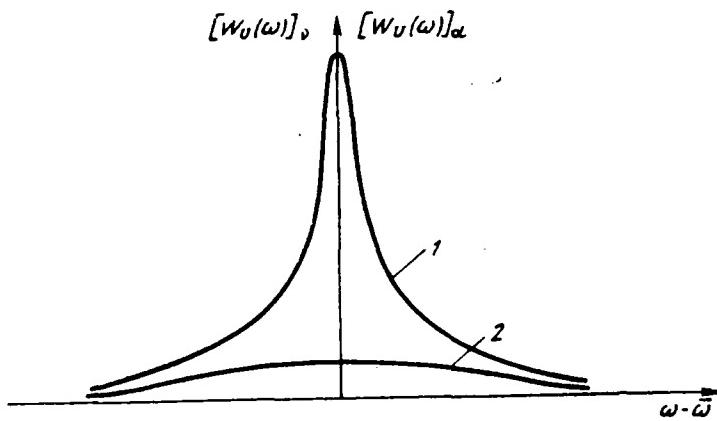
Fig. 2.11.   components of energy spectrum of fluctuating oscillation, connected with fluctuations of frequency $[W_U(\omega)]_\nu$ (curve 1) and fluctuations of amplitude $[W_U(\omega)]_\alpha$ (curve 2).   For the clarity the components indicated are depicted in different scales. With the image on the identical scale component $[W_U(\omega)]_\alpha$ would be forced against the axis of abscissas.

Page 107.

In certain cases it is necessary to know additionally the degree of the correlation of honey by the fluctuations of frequency and amplitude.  As it was shown above, through the spectral densities of fluctuations is determined the spectral line width of the oscillation of generator; knowing them, it is possible to calculate also the mean square of phase change in the assigned interval of time [46]. Therefore the spectral densities of the fluctuations of frequency and amplitude can be accepted as the fundamental parameters, which characterize noisiness of generators [62, 64].
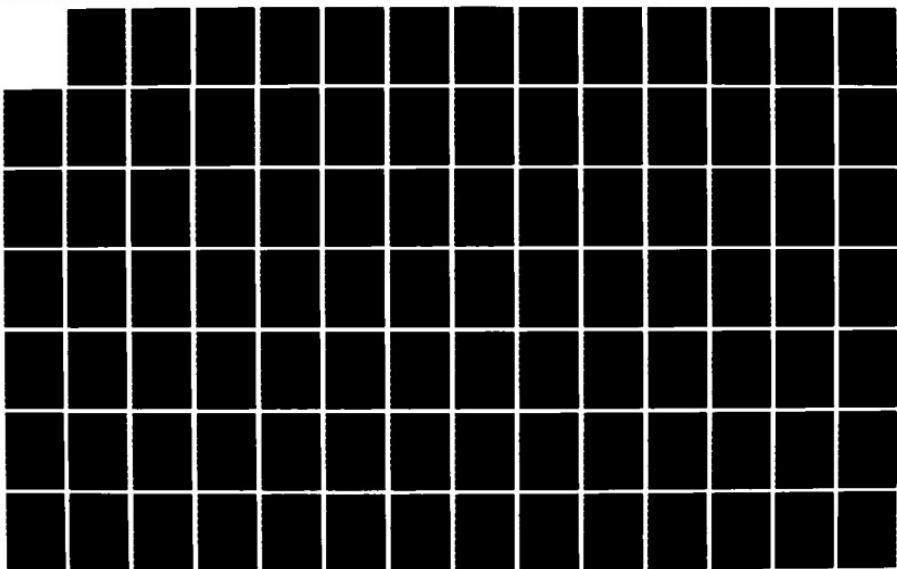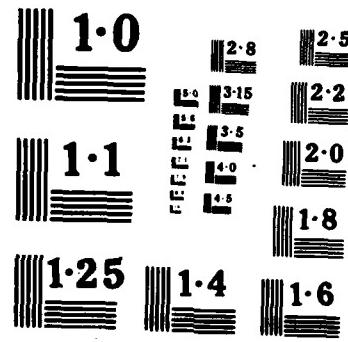
This method of describing fluctuation properties of generators frequently is utilized in technical literature both in theoretical and in experimental works. Since data of experiments are represented sometimes and in another form, one should dwell on the question of processing experimental data.

Straight/direct result of changes it is not spectral density, but mean squares (power) of fluctuations in after transmission $\Delta F_c$ of analyzer of spectrum $\overline{|a(t)|^2}_{\Delta F_c}$, $\overline{|v(t)|^2}_{\Delta F_c}$. Approximate values of spectral densities are obtained further by the division of these values on $\Delta F_c$, i.e.

$$W_a(F) \approx \frac{\overline{|a(t)|^2}_{\Delta F_c}}{\Delta F_c},$$

$$W_v(F) \approx \frac{\overline{|v(t)|^2}_{\Delta F_c}}{\Delta F_c}, \qquad (2.20)$$

where F - frequency of tuning/adjusting the spectrum analyzer, and $\Delta F_c$ - its passband, expressed in hertz. It would be possible to obtain precise values of spectral densities only with the infinitesimally narrow passband of the spectrum analyzer, since

$$W_a(F) = \lim_{\Delta F_c \to 0} \frac{\overline{|a(t)|^2}_{\Delta F_c}}{\Delta F_c},$$

$$W_v(F) = \lim_{\Delta F_c \to 0} \frac{\overline{|v(t)|^2}_{\Delta F_c}}{\Delta F_c}.$$

Such measurements are in principle impossible due to the fact

that they would require infinite time, even if filter with infinitesimally narrow band was realized.

Page 108.

Therefore, speaking about the experimental values of the spectral densities of fluctuations, we always imply their approximate values, determined on the mean squares of fluctuations, measured in the final frequency band.

More frequently use not spectral density of fluctuations of angular frequency $\nu(t)$, but usual $\delta f(t)$. Since $\delta f(t) = \nu(t)/2\pi$, then

$$W_f(F) = \frac{W_\nu(F)}{(2\pi)^2} \approx \frac{\overline{|\delta f(t)|^2_{\Delta F_c}}}{\Delta F_c}. \qquad (2.21)$$

Since value $\overline{|\alpha(t)|^2_{\Delta F_c}}$ is dimensionless [let us recall that $\alpha(t) = \delta U(t)/\vec{U}$ – relative fluctuation of amplitude], while $\overline{|\delta f(t)|^2_{\Delta F_c}}$ it has dimensionality [Hz $^2$], dimensionalities $W_\alpha(F)$ and $W_f(F)$ will be [1/Hz] and [Hz$^2$/Hz] respectively.

Utilized in practice spectrum analyzers have passbands from ones hertz at lowest frequencies of Doppler range (ten hertz) to several kilohertz on averages in high frequencies (ten and hundreds of kilohertz). The selection of the passband of the spectrum analyzer is dictated by two contradictory considerations: on one hand, it must be possibly already so that the parts of the spectrum correctly would be reproduced, and on the other - as it is wide as possible for

shortening of the time of measurement and increase in the accuracy of reading, since during the expansion of passband decreases the time of establishment and measuring error due to the natural instability of readings/indications of the indicator (see S 2 this chapter). Therefore the passband of the spectrum analyzer is selected as a result of a compromise between two named requirements.

Obviously, reproduction of form of spectrum being investigated will be satisfactory, if in limits of passband of analyzer spectral density is changed not too strongly. During the analysis at the low frequencies, where a change in the spectral densities due to the flicker effect is observed, passband must be narrow, and the narrower it is, the less the frequency of tuning/adjusting analyzer; at the high frequencies, where the spectral density of fluctuations becomes uniform it is possible to substantially expand passband.

Aforesaid remains valid, if in spectra there are no regular components. But if they are present, then the passband of the spectrum analyzer is dictated by the possibility of their discrimination against the background of "flat" noise.

Page 109.

In the literature are encountered different methods of the recording of results of spectral measurement of fluctuations:

1. Are indicated the mean squares of the fluctuations of amplitude and frequency in the passband of the spectrum analyzer,

which was being utilized in measurements $\overline{|a(t)|^2_{\Delta F_c}}$ and $\overline{|\delta f(t)|^2_{\Delta F_c}}$, and is

given the value of passband $\Delta F_c$. This method of the recording of the

results of experiment is objective; however, it is inconvenient fact

that for the comparison of data, published in different sources, for

the reader it is necessary to fulfill work on bringing of results to

one band of analysis.

2. Are communicated not straight/direct results of measurements,

but referred to standard frequency band, as which accept band 1 Hz or

1 kHz. Evidently, the most convenient value of standard band are $\Delta F=1$

Hz, since in this case communicated data approximately correspond to

the spectral densities of the mean squares of fluctuations $W_a(F)$ and

$W_f(F)$. For so that it would be possible to judge the accuracy of

reproduction of the parts of the spectra, it is desirable to give the

value of the passband of the analyzer of spectrum, which was being

utilized while conducting of measurements.

3. In some, predominantly foreign, sources are communicated not

mean squares of fluctuations, but standard deviations [1]:

$$\sigma_a(F) = \sqrt{\overline{|a(t)|^2_{\Delta F_c}}},$$

$$\sigma_f(F) = \sqrt{\overline{|\delta f(t)|^2_{\Delta F_c}}}.$$

FOOTNOTE [1]. In the technical literature of the USA for the

designation of standard deviations is utilized the reduction "rms"

(ratio medium square), that analogous with the term "root-mean-square

value", used in the Soviet literature together with the term "standard

deviation". ENDFOOTNOTE.

This method of the recording of data of experiment seems unsuccessful, since for calculating the fluctuation parameters of systems, which contain generator, or width of its spectral line it is necessary to convert $\sigma_a(F)$ and $\sigma_f(F)$ into the spectral densities of the mean squares.

Let us give example of translation/conversion of standard deviation of fluctuations of frequency to mean square, in reference to band 1 Hz (approximate spectral density of mean square of fluctuations of frequency). Let $\sigma_f = 10$ Hz in the band of frequencies $\Delta F_c = 100$ Hz. Then, obviously,

$$W_f = \frac{\sigma_f^2}{\Delta F_c} = 1 \ \text{Hz}^2/\text{Hz}.$$

Page 110.

1.3. Relation of the power of the side components of the spectrum of the fluctuating oscillation to the average/mean power of oscillation.

In number of cases it is convenient to characterize fluctuating oscillation by ratio of power of lateral spectral components of amplitude and frequency modulation in certain narrow band of frequencies $\Delta F$ at a distance of F from medium frequency of oscillation to its average/mean power. For the components this relation of amplitude modulation it is given by formula (2.6)

$$\frac{[P_0(F)]_{\Delta F}}{P_0} = W_a \Delta F.$$

Let us recall that $|P_6(F)|_{2\Delta F}$ - power of side components of amplitude modulation in two bands with width of $\Delta F$ each, arranged/located symmetrically relative to medium frequency of oscillation (Fig. 2.12a). In practice they are more frequently interested in the power, which falls to one sideband $\Delta F$. Designating relation $\dfrac{|P_6(F)|_{\Delta F}}{P_0}$ by symbol $|\gamma_a(F)|_{\Delta F}$, we have

$$|\gamma_a(F)|_{\Delta F} = \frac{W_a(F)\,\Delta F}{2}. \qquad (2.22)$$

Usually parameter $|\gamma_a(F)|_{\Delta F}$ is called ratio of power of amplitude noise in band $\Delta F$ to carrier output.
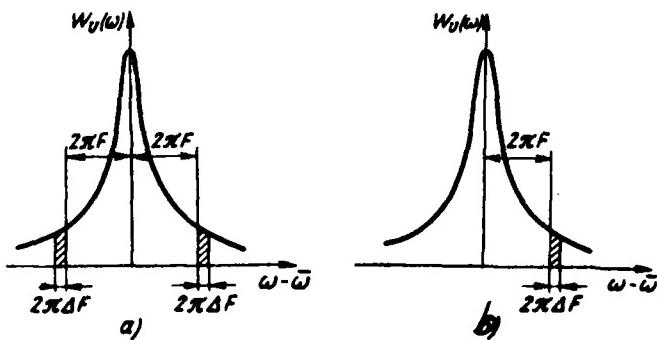
Fig. 2.12.  On calculation of relation of power of side components of spectrum of fluctuating oscillation to average/mean power of oscillation:  (a) to two sidebands, (b) to one sideband.

Page 111.

This is inaccurate, since the power of the frequency modulated oscillation is distributed in the frequency band, which makes it possible to speak only about the average/mean power of oscillation. Let us note that in view of the low values of the low values of the fluctuations of the amplitude of real generators it is possible to consider the average/mean power of oscillation which does not depend on the level of amplitude noise, since its contribution is very small.

Most frequently take $\Delta F$ as equal to 1 kHz or 1 Hz.  Latter/last more preferable, since in this case right side (2.22) is numerically equal to half of the spectral density of the mean square of the relative fluctuations of amplitude.  With $\Delta F$=1 Hz we will omit index "$\Delta F$":

$$\gamma_a(F) = |\gamma_a(F)|_{1\,\text{Hz}} = \frac{W_a(F)}{2} \cdot 1\,\text{Hz}. \qquad (2.23)$$

Key:  (1).  Hz.

Obviously parameter $\gamma_a\,(F)$ is dimensionless.  In the literature value $\gamma_a(F)$  frequently is indicated in the decibels;

$$[\gamma_a(F)]_{db} = 10\lg\left\{\frac{W_a(F)}{2}\cdot 1\ {}^{(1)}_{zц}\right\}. \qquad (2.24)$$

Key:  (1).  Hz.

It is possible to determine ratio of power of components of frequency modulation in one sideband to average/mean power of oscillation analogously.  From formula (2.18) it follows:

$$[\gamma_f(F)]_{\Delta F} = \frac{[P_6(F)]_{\Delta F}}{P_0} = \frac{W_f(F)\Delta F}{2F^2} = \frac{W_\varphi(F)\Delta F}{2}. \qquad (2.25)$$

For the brevity we will call $[\gamma_f(F)]_{\Delta F}$  the ratio of the power of frequency noise in the band $\Delta F$ to the average/mean power of oscillation.  With $\Delta f = 1$ Hz

$$\gamma_f(F) = [\gamma_f(F)]_{1\ zц} = \frac{W_f(F)}{2F^2}\cdot 1\ {}^{(1)}_{zц} = \frac{W_\varphi(F)}{2}\cdot 1\ {}^{(1)}_{zц}. \qquad (2.26)$$

Key:  (1).  Hz.

In this case parameter $\gamma_f(F)$ is numerically equal to half of the spectral density of the mean square of the fluctuations of phase. Parameter $\gamma_f\,(F)$  is dimensionless and the value of it frequently also is assigned in the decibels:

$$[\gamma_f(F)]_{db} = 10\lg\left\{\frac{W_\varphi(F)}{2}\cdot 1\ {}^{(1)}_{zц}\right\}. \qquad (2.27)$$

Key;  (1).  Hz.

Let us note that formula (2.18), from which it follows (2.25) and (2.26), is valid only for frequencies F, which considerably exceed width of the spectral line of oscillation.

Page 112.

In § 1.1. on the chapter confronting was given an example of the calculation of the spectral line width of klystron oscillator of the range of microwaves; it proved to be equal to 12.5 Hz.  On the larger level of frequency noise it is possible to obtain numerals on the order of hundreds hertz.  Therefore parameter $\gamma_f(F)$, designed on the measured spectral density of the mean square of the fluctuations of frequency $\gamma_f(F) = \dfrac{W_f(F) \cdot 1}{2 F^2}$ Hz, can be interpreted as the ratio of the power of frequency noise in the band 1 Hz to the average/mean power of oscillation only for frequencies F on the order of $10^3$ Hz and above. At lower frequencies $\gamma_f(F)$ one ought not to identify with the relation indicated; it is simply equal to half of the mean square of the fluctuations of phase in the band 1 Hz.

Difference between spectral course of ratio of power of frequency noise to average/mean power of oscillation and spectrum of fluctuations of phase is shown in Fig. 2.13.

Let us note that with uniform spectra of fluctuations of amplitude and frequency $\gamma_a F = \text{const}$, while $\gamma_f(F)$ is proportional to $1/F^2$. In the region of the effect of the flicker effect, where $W_a(F)$ and $W_f(F)$ are proportional $1/F$, $\gamma_a(F)$ and $\gamma_f(F)$ proportional $1/F$ and $1/F^3$ respectively.

Characteristic of fluctuation properties of generators by parameters $W_a(F)$ and $W_f(F)$ or $\gamma_a(F)$ and $\gamma_f(F)$ is equivalent, since between them there is mutual one-to-one correspondence.  However, it

seems to us that during the physical investigations to more preferably express results with spectral densities $W_1(F)$ and $W_I(F)$. Matter in the fact that in this case the flicker effect is developed in both spectra in the form of the sections, whose frequency course coincides with the frequency course of flicker noise in the currents of instrument, which makes it possible to easily isolate the region of its action.

$$\frac{W_{\varphi}|F|\Delta F}{2[P_{\delta}|F|]_{\Delta F}}{P_{\partial}}$$
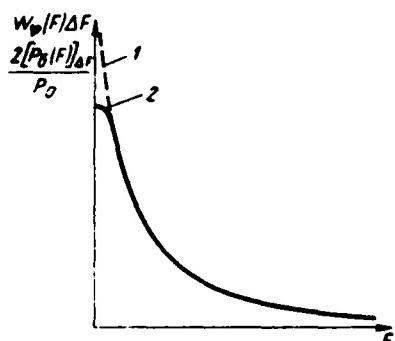
Fig. 2.13. Course of energy spectrum of fluctuations of phase (1) and relative power (2) side component frequency modulation (reproducing with small F duct/contour of spectral line): In first case by F is understood frequency of fluctuations, the secondly - distance from sideband in question to carrier frequency.

Page 113.

2.  Methods of measuring the amplitude and frequency noises.

2.1.  Single-channel method of straight/direct detection.

Method of straight/direct detection is simplest method of level measurement of fluctuations of amplitude or frequency. The block diagram of the single-channel meter, which works according to this principle, is depicted in Fig. 2.14. Those investigated shf oscillation are supplied to the input of amplitude or FM discriminator. Envelope at the output of detector reproduces with respect to the fluctuation of amplitude or frequency. Further the voltage/stress of envelope enters the input of the low-noise amplifier, which has the band, sufficient for the transmission of the

required frequency band of the fluctuations (usually this range it

encompasses frequencies from ten - hundred hertz to hundreds of

kilohertz).  The intensive voltage/stress is supplied to the analyzer

of spectrum, with the aid of which is conducted the spectral

investigation of fluctuations.  At the output of the spectrum analyzer

stands the indicator, whose readings/indications are proportional to

the power (the mean square) of noise in the filter pass band of the

spectrum analyzer.  For obtaining the quantitative results the meter

must be supplemented by one or another device/equipment for

calibrating the absolute level of the noises being investigated.


Let us examine general requirements for elements of network of

meter.


Shf detector.  Since the FM discriminator is the combination of

the frequency discriminator of one or the other form and amplitude

detector, let us pause at first at the requirements for the latter.

Its inherent noise and conversion loss must be small.  The first

requirement is obvious - with small noises of noise generator of

detector limit the sensitivity of meter.  The second requirement comes

from the fact that with the large conversion loss the role of

amplifier noises, which follows after the detector, grows/rises, which

also decreases in the sensitivity of meter.


It is important to note that detection of envelope occurs

virtually without distortions with any form of volt-ampere

characteristic of detector, since low value of fluctuations of amplitude of shf oscillation in comparison with its average/mean value always provides precise reproduction of envelope of shf oscillation with voltage/stress on load of detector.  Conversion loss during the detection of the weakly modulated oscillation are equal to the certified/rating conversion loss in the mixing mode/conditions [1], reduced doubly (in contrast to the mixing mode/conditions during the amplitude detection the output voltage/stress of detector caused by two sidebands of modulation).

FOOTNOTE [1].  If carrier output is equal to the power of heterodyne, stipulated in the certificate.  ENDFOOTNOTE.

| (1) | (2) | (3) | (4) | (5) |
|---|---|---|---|---|
| СВЧ вход | Амплитуд-ный или частотный детектор | Малошумя-щий усилитель | Анализа-тор спектра | Индикатор мощности шума |
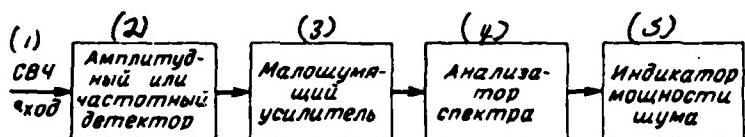
Fig. 2.14.  Block diagram of single-channel meter of fluctuations of amplitude, constructed according to principle of straight/direct detection.

Key:  (1).  Shf input.  (2).  Amplitude or FM discriminator.  (3). Low-noise amplifier.  (4).  Spectrum analyzer.  (5).  Power- level indicator of noise.

For measuring noises low-powered generators by most adequate/approaching detector crystal diode is. The optimum mode/conditions of detection is provided in this case at the power shf signal, supplied to the detector, on the order of 0.5-1 mW; in this case the conversion loss are 4-6 dB. Unfortunately, the inherent noise of crystal diodes are sufficiently great, and precisely they limit the sensitivity of measurements at the low frequencies. An unpleasant circumstance is the fact that the inherent noise level of detector depends on the power shf oscillation, that their effect on the results of the measurement via the cutoff/disconnection of the investigated generator from the meter does not make it possible to consider.

Spread of noise characteristics of crystal diodes is very great even in limits of one type of diodes; therefore it is necessary to select/take diodes before their installation into measuring circuit. Silicon diodes possess the best noise parameters at the low frequencies. The characteristic form of intrinsic noise spectra of diode at shf power on it, equal to 0.5 mW, it is shown in Fig. 2.15.

At frequencies of below 20 kHz dominant role plays surplus noise of p-n junction; therefore the sensitivity of meter of fluctuations is nonuniform along spectrum, being reduced with decrease of frequency. Let us note that the inherent noise level of crystal diodes increases with an increase in the negative bias/displacement. This limits the

resistance/resistor of the load of detector with value into several hundred ohms.

If power of investigated generator is sufficiently great (watts, tens of watts), it is possible to utilize for detection vacuum- tube diode of corresponding frequency range. Their own low-frequency noises (flicker noises) of the vacuum-tube diodes are less than crystal; however, for obtaining the sufficiently low conversion loss on them it is necessary to supply the considerably greater shf power (hundreds of milliwatts) and to utilize high resistance/resistors of load (tens of kilohms). Diodes of the shf range with oxide cathodes produced by industry (for example, 6D13D) make it possible to increase the sensitivity of the measurement of the fluctuations of amplitude by value on the order of 10 dB [1].

FOOTNOTE [1]. According to the data, obtained by A. S. Karasev. Since the parameters of diodes have considerable spread, then for the realization of high sensitivity diodes must be selected/taken. ENDFOOTNOTE.

Everything said above related to measurement of fluctuations of amplitude. For measuring the fluctuations of frequency the diagram is supplemented by the frequency discriminator, which is established/installed before shf detector. The designation/purpose of discriminator consists of the conversion of the fluctuations of frequency in the fluctuation of amplitude. Obviously the sensitivity

of the measurement of the fluctuations of frequency is determined not only by the sensitivity of the meter of the amplitude noise, established/installed after discriminator, but also by the slope/transconductance of the amplitude frequency characteristic of discriminator.

Detuned reentrant cavity (Fig. 2.16a) is simplest frequency discriminator. In this diagram the effect of frequency detection is caused by the dependence of the transmission gain from the frequency, supplied to the resonator. Obviously the effectiveness of frequency detection grows/rises with an increase in the quality of resonator.
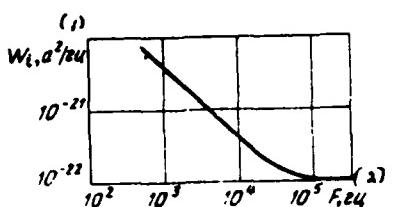
Fig. 2.15.  Low-frequency noise spectrum of shf detector on silicon diode.

Key:  (1).  a²/Hz.  (2).  Hz.

Page 115.

The greatest slope/transconductance of amplitude-frequency characteristic is reached at tuning of resonator to the point of half transmission factor according to the power (with respect to the transmission factor in the presence of the resonance).  Let us note that with an increase in the quality of resonator the band of frequencies of the fluctuations, in which discriminator works without the distortions, is reduced.  It is considered that the distortions are negligible in the frequency band, which does not exceed 10% of the passband of resonator.

Interference (Fig. 2.16b) is is a more complex circuit of FM discriminator.  In this case the oscillation being investigated is divided into two channels, in one of which is established/installed the element/cell, which converts the fluctuations of frequency in the fluctuation of phase.  Such element/cell can be, in particular, the resonator, tuned for the medium frequency of the oscillations (it is utilized its phase-frequency characteristic, i.e., the dependence of

the phase of transmission factor on the voltage/stress from the
frequency). Oscillations from outputs of both channels are supplied
to the phase discriminator, which converts the fluctuations of a phase
difference of oscillations in the fluctuation of the amplitudes, which
then are measured.

Interference schematic of FM discriminator makes it possible to
obtain additional gain in sensitivity of measurement of fluctuations
of frequency, when power of generator being investigated noticeably
exceeds power, necessary for guaranteeing optimum conditions for work
of amplitude of shf detector (0.5-1 mW). The fact is that, possessing
the excess of input power, it is possible to phase the oscillations,
which enter the input of phase discriminator so that their
interference would occur with the effect of a deep suppression (to the
power level, amplitude detector necessary for the work).
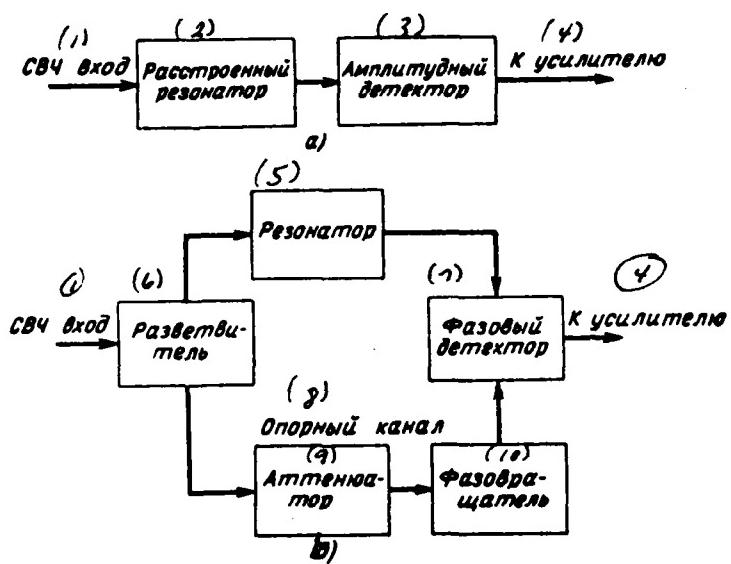
Fig. 2.16. Block diagrams of shf FM discriminators: a) by frequency discriminator in the.form of detuned reentrant cavity; b) interference type.

Key: (1). shf input. (2). Detuned cavity. (2). Amplitude detector. (4). To amplifier. (5). Resonator. (6). Splitter. (7). Phase discriminator. (8). Supporting channel. (9). Attenuator. (10). Phase inverter.

Page 116.

In this case proportionally the degree of suppression increases the relation of the power of the fluctuations of phase, caused by the action of resonator in one of the channels, to the average/mean power of oscillation, i.e. in the final analysis the slope/transconductance of the frequencies leg detector increases.

Practical implementation of interference FM discriminator can be

different:  it is possible to construct it, utilizing reentrant

cavity, as shown in Fig. 2.16b, resonator, which works for reflection,

or use delay line (method of Berstein [47].

Low-noise amplifier.  Fundamental requirements for the amplifier

(in addition to guarantee of necessary of passband to amplification

factor) consist of obtaining of the low values of the levels of

pulsations and inherent noise.  If the lowest frequency of passband

lies/rests at the region of several kilohertz, then amplifier can be

constructed on vacuum lamps with an electronic-stabilized rectifier.

For decreasing the level of the pulsations, caused by the harmonics of

network/grid, the amplifier is supplied with the powerful/thick

circuits of anodic decouplings; in certain cases it is necessary to

supply the incandescence/filament of the first tubes by direct

current.

Decrease of inherent noise is achieved by use of low-noise tubes

with high slope/transconductance in first cascade/stage (6Zh9P or

6Zh11P in triode inclusion) and metallic resistors in those circuits

of input cascades/stages, where dc current component occurs.

If requirement of measurement of fluctuations at lower

frequencies (ten, hundred hertz) is placed, then rationally utilize

transistor amplifiers, supplied from dry batteries.  This

removes/takes the problem of pulsations.  As far as inherent noise

level is concerned, during the rational construction of amplifier and

the use in the input cascades/stages of the contemporary low-noise
transistors (for example P28, P313) it is possible to obtain the
results, which are not inferior to those, which are achieved/reached
in the vacuum-tube amplifiers.

Spectrum analyzer and power-level indicator of fluctuations.
Requirements for the characteristics of these network elements are
closely related and therefore we will examine together them.

For indication of power level of noise at output of spectrum
analyzer it is most convenient to utilize quadratic voltmeter with
averaging (integrating) filter.  An example of the device/equipment of
this voltmeter is shown in Fig. 2.17.  Diode is in this case the
nonlinear element/cell, which detects noise.  If the dependence of the
current of diode on the applied voltage/stress is quadratic, then the
constant component of rectified current is geometric mean square
(power) of the noise voltage applied to the diode.  for registering
its value the dial instrument is utilized.

Besides constant component in current of detector are contained
variable, random components, whose spectrum differs from noise
spectrum supplied to detector due to nonlinear conversions during
detection.  Thus, for example, if the energy spectrum of subject on
the input of the detector of noise voltage/stress has rectangular
form, then the energy spectrum of the current of detector with the
quadratic and the characteristic takes the form, depicted in Fig.

2.18b.


It consists of line on zero frequency ( constant component, whose level it is standard/criterion of power of detected noise) and two sections with continuous spectrum.  One of them by width $\Delta F_c$ ($\Delta F_c$ - the width of the original spectrum) adjoins the zero frequency.  Spectral density changes in this section according to the linear law, growing/rising to the low frequencies.
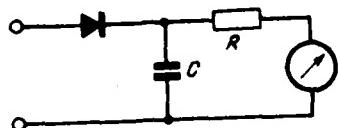
Fig. 2.17.  Simplest indicator circuit of power of noise.

Page 117.

The second section is localized in the vicinity of the double

frequency of tuning/adjusting the spectrum analyzer and on the form

reproduces the spectrum of initial noise voltage/stress.  It is not

difficult to explain this transformation of the spectrum.


Let us select two elementary components of initial spectrum of

fluctuations and let us trace their fate during quadratic conversion:

$$(a_1 \cos \Omega_1 t + a_2 \cos \Omega_2 t)^2 = \frac{a_1^2 + a_2^2}{2} + a_1 a_2 \cos (\Omega_1 - \Omega_2) t +$$

$$+ a_1 a_2 \cos (\Omega_1 + \Omega_2) t + \frac{a_1^2}{2} \cos 2\Omega_1 t + \frac{a_2^2}{2} \cos 2\Omega_2 t.$$

The first member of the right side of this expression is constant

component, the second - low-frequency differential combination

oscillation.  Its minimum frequency adjoins the zero, if the

frequencies of selected elementary components are close in the value,

and maximum - to frequency $u_{\text{макс}} = 2\pi \Delta F_c$, since it can be obtained with

the greatest separation of frequencies $\Omega_1$ and $\Omega_2$, limited by the band

of initial spectrum $[(\Omega_1 - \Omega_2)_{\text{макс}} = 2\pi \Delta F_c]$.


During joint action of many elementary component number possible

differential oscillations is the greater, the less difference in

frequencies of selected components.  Therefore in the frequency

section in question spectral intensity must decrease in proportion to

removal/distance from the zero frequency, becoming zero when $\Omega = 2\pi\Delta F_c$.

The latter/last three members of the recorded above expression

appeared due to the total combined effects:  it is not difficult to

see that the region of their manifestation was included between the

frequencies, distant behind the double frequency of tuning/adjusting

the spectrum analyzer to the value of its passband.

Fluctuations of current of detector cause instability of

readings/indications of needle indicator and thereby they limit

accuracy of measurement of the constant component.  In order to

decrease their effect, filtration is utilized.  In Fig. 2.17

elements/cells of the integrating low-pass filter is the capacitance

of capacitor C, connected in parallel to indicator instrument, and the

resistor/resistance of instrument R.  Obviously the spectral section

of fluctuations, which adjoins the zero frequency, presents the

greatest danger; fluctuations at the double frequency of

tuning/adjusting of the analyzer of the spectrum are filtered easily,

yes even their action on the readings is considerably weakened due to

the mechanical inertia of arrow system.
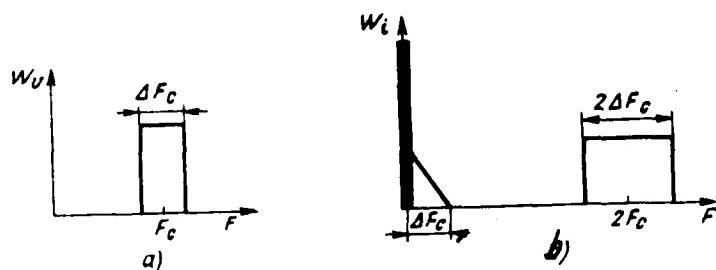
Fig. 2.18.  Energy spectra:  a) voltage on input of square law detector, b) current of detector.

Page 118.

Thus, we come to conclusion that accuracy of reading of dc current component of detector increases with decrease of passband of RC-filter, since in this case band (and consequently, and power) of fluctuations in current of indicator instrument decreases.  However, the contraction of the passband of RC-filter indicates an increase in its time constant $\tau_0$=RC, i.e.  increases the time of the establishment of the current through the instrument or, in other words, the time of measurement.

Let us examine dependence of accuracy of reading on value of passband of analyzer of spectrum $\Delta F_i$ (noise bandwidth, supplied to detector).  If the spectral density of the mean square of noise voltage on the input of detector is equal to $W_U$, and the spectrum has rectangular form, the dc current component of detector is equal to $I_0 = SW_U \Delta F_c$, where S - coefficient, which determines the characteristic of the detector:  $I=SU^2$.  If we increase $\Delta F$, then for maintaining the previous reading/indication of detector it is necessary to decrease

the stress level on its input, i.e., to decrease $u_f$. In this case the

power of fluctuations in the low-frequency part of the spectrum also

must decrease, since, remaining as a whole of constant/invariable, it

will be dispersed in the more broadband.  This means that in the

constant/invariable parameters of RC-filter the level of the

fluctuations, passed by it, will be lowered, i.e. the accuracy of

measurement will rise.  The aforesaid is explained by Fig. 2.19, in

which are shaded the regions of the spectrum of fluctuations, which

fall into the passband of RC-filter.


Mathematical analysis gives following expression for relative

error of readings/indications of indicator examined:

$$a = \frac{1}{\sqrt{2\tau_0 \Delta F_c}} , \qquad (2.28)$$

where $\tau_0$=RC - time constant RC-filter, and $\Delta F_c$ - passband of spectrum

analyzer.  Thus, for example, with $\tau_0$=1 s and $\Delta F_c$=100 Hz $\alpha$=7%; if this

accuracy of reading is insufficient and increase $\Delta F_c$ is undesirable

according to one or the other considerations, then to increase

accuracy of reading is possible only with the value of an increase in

the time of measurement.  With $\tau_0$=10 s we obtain $\alpha$=2%.
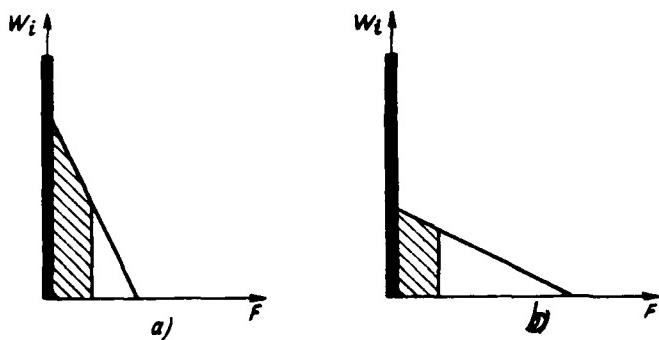
Fig. 2.19. Low-frequency part of energy noise spectrum in current of square law detector with narrow (a) and broad (b) band of fluctuations of voltage/stress, supplied to input of detector.

Page 119.

Considerable increase in time of measurement is undesirable, since this impedes conducting experiments and requires special measures for maintenance of operational stability of entire equipment during measurement. This sets limitation on the minimum value of the passband of the analyzer of spectrum $\Delta F_c$. Maximum value $\Delta F_c$ is determined by the requirement of the reproduction of the parts of the spectra being investigated. Usually $\Delta F_c$ is selected not more than $(0.1-0.2)F$, where F - frequency of tuning/adjusting the spectrum analyzer. Hence follows that constant value $\tau$, the accuracy of reading will decrease with the decrease of frequency. But if we assign error identical at all frequencies, then this will lead to the need for an increase in the time of measurement at the low frequencies.

Let us note that in spectrum of fluctuations regular components can be present.  For their isolation/liberation and precision determination of level the supplementary contraction of the passband of the spectrum analyzer can be required, even if the discussion deals with the high frequencies of fluctuations.  Therefore during the design of the meter of noise it is desirable to provide the possibility of bandwidth control of the analyzer of spectrum and time constant of RC-filter in the sufficiently wide limits.

Sensitivity of single-channel meter of fluctuations of amplitude is limited to noise level of crystal detector and noises of input amplifier stage; primary meaning at low frequencies has surplus noise of detector.  Since the noise level of detector depends on the power of the shf oscillation supplied to it, it is not possible to consider the effect of the noises of meter on the result of observation from reading/indication of indicator at the off shf power.  From this it follows that recording the level of the fluctuations of amplitude can be confident only then, when it exceeds the noise of detector several times.  Otherwise the doubt remains:  are readings/indications of indicator caused by inherent noise of measuring device.  The best crystal detectors of shf range are capable of ensuring the sensitivity of the measurement of the single-channel meter of order -130 dB at frequencies of fluctuations on the order of $10^3$ Hz and -140 dB at frequencies on the order of $10^5$ Hz [1] (by sensitivity is understood minimum confidently recorded level $\gamma_a (F) - [\gamma_a (F)]_{мин}$).

FOOTNOTE [1].  At the high frequencies of fluctuations the sensitivity is limited as a rule to amplifier noises.  ENDFOOTNOTE.

Let us note that in view of the instability of the parameters of crystal detectors level measurements $\gamma_a (F)$, close to the maximum, are unreliable.

Sensitivity of single-channel meter of fluctuations of frequency is limited, as noted above, not only inherent noise of detector and amplifier, but also by slope/transconductance of discriminator used. If the latter is that detuned to the half-power point of resonator, then the minimally measurable level of the spectral density of the mean square of the fluctuations of frequency is equal to

$$[W_f(F)]_{\text{мин}} = \left(\frac{\overline{f}}{Q_\text{н}}\right)^2 [W_a(F)]_{\text{мин}},$$

where $Q_\text{н}$ - quality of the loaded resonator, and  $[W_a(F)]_{\text{мин}}$ - minimally measurable level of the spectral density of the fluctuations of amplitude.  With $Q_\text{н} = 10^4$ and $\overline{f} = 10^{10}$ Hz at frequency F on the order of $10^3$ Hz, i.e., when $[\gamma_a(F)]_{\text{мин}} = 10^{-13}$, we obtain  $[W_f(F)]_{\text{мин}} = 10^{-1}$ Hz$^2$/Hz.  At frequency F on the order of $10^5$ Hz, i.e., when $[\gamma_a(F)]_{\text{мин}} = 10^{-14}$, we will obtain $[W_f(F)]_{\text{мин}} = 10^{-2}$ Hz$^2$/Hz.

Page 120.

During use of interference FM discriminator sensitivity is raised:  gain is determined by relation of power input and output of discriminator of phase.  As it was already said, this gain can be realized only then, when the generator being investigated has a power,

which exceeds the power, necessary for operational provisions of amplitude of shf detector.

Let us note that given evaluations/estimates are valid until amplitude noise of generator being investigated is sufficiently small and masks effect of frequency detection. Otherwise the sensitivity of the measurement of the fluctuations of frequency is limited to the level of amplitude noise, and its effect must be considered.

Detailed study of problem of measurement of fluctuations of frequency, which includes analysis of properties of frequency discriminators of different types, reader will find [46, 48, 49].

In conclusion let us pause at calibration of meters of fluctuations. The most convenient method of calibration is the use of a modulator of amplitude or frequency (phase), established/installed in shf circuit, which connects the generator being investigated with the meter of the fluctuations of amplitude or frequency. As the modulators ferrite element/cell [50] or crystal diode, which works can be used to the reflection in the mode of key/wrench and connected with the fundamental circuit by the coupler of power [1].

FOOTNOTE [1]. A calibrator of such type is proposed by S.S. Karatetskiy. ENDFOOTNOTE.

Both the forms of modulators - self-calibrating indicated. In the

literature the modulators, intended for low-level creation of
modulation, are called micro-modulators.

To calibrate meter of fluctuations is possible with the aid of  . _
low-frequency signal generator (noise), by action of which they
replace action of detected fluctuations.  In this case it is necessary
to additionally know the conversion loss of detector, and in the
measurement of the fluctuations of frequency - slope/transconductance
of discriminator.

Let us add that during study of generators with electronic
retuning of frequency calibration in measurement of fluctuations of
frequency it is easy to carry out supplying gauging electrode voltage,
which controls oscillator frequency, and finding deviation of
frequency through known slope/transconductance of electronic
tuning/adjusting.

2.2.  Two-channel (correlation) method of measuring the fluctuations.

Sensitivity of single-channel meter of fluctuations of amplitude,
as a rule is insufficient for study of noises of contemporary
generators.  The construction of meter according to two-channel
diagram makes it possible to substantially increase the sensitivity of
measurements.  The operating principle of the two-channel meter of the
fluctuations of amplitude is explained by the block diagram, depicted
in Fig. 2.20.

Oscillations of investigated generator with the aid of splitter of power are supplied to two independent measuring channels, each of which consists of shf detector and low-noise amplifier with band, which encompasses studied frequency range of fluctuations. Output potentials of these channels contain correlated components, caused by detection of the amplitude noise of the investigated generator, and can be recorded the form:

$$U_\text{I}(t) = U_1(t) + U_a(t). \quad U_\text{II}(t) = U_2(t) + U_a(t),$$

where $U_1(t)$ and $U_2(t)$ - components, caused by the inherent noise of measuring channels (among other things by noises of shf detectors), and $U_a(t)$ - coherent component of noise, which is present in the voltages/stresses of channels as a result of detection of the fluctuations of the amplitude of generator.

Page 121.

Its level remains to be determined. Expressions are recorded under the assumption that the amplification of channels is controlled so, that the level of coherent component at their outputs is identical. Let us note that $U_1(t)$, $U_2(t)$ and $U_a(t)$ is mutually not correlated (they they are caused by the independent noise sources). Changing the polarity of output voltage/stress of one of the channels, we can obtain on the output of summator sum or voltage difference $U_\text{I}(t)$ and $U_\text{II}(t)$ (for the sake of simplicity let us assume that the transmission factor of the inverter of phase and summator it is equal to one):

$$U_+(t) = U_1(t) + U_2(t) + 2U_a(t), \quad U_-(t) = U_1(t) - U_2(t).$$

Formed thus signals are passed then through spectrum analyzer, which isolates of them specific frequency components. It would be possible to analyze the spectrum in the independent channels to the commutator; however, this solution is uneconomic, since it would require two identical spectrum analyzers instead of one in the diagram in Fig. 2.20. It is not difficult to ascertain that both versions are equivalent according to the result of their action as a result of the linearity and the section of meter in question.

Let us designate output potentials of spectrum analyzer upon total and differential inclusion/connection of inverter of phase through

$$u_+(t) = u_1(t) + u_2(t) + 2u_a(t), \quad u_-(t) = u_1(t) - u_2(t).$$

These voltages/stresses are supplied to the square law detector, as a result of which we obtain two readings of the power-level indicator of noise, proportional

$$\overline{u_+^2(t)} = \overline{u_1^2(t)} + \overline{u_2^2(t)} + \overline{4u_a^2(t)} \quad and \quad \overline{u_-^2(t)} = \overline{u_1^2(t)} + \overline{u_2^2(t)}.$$
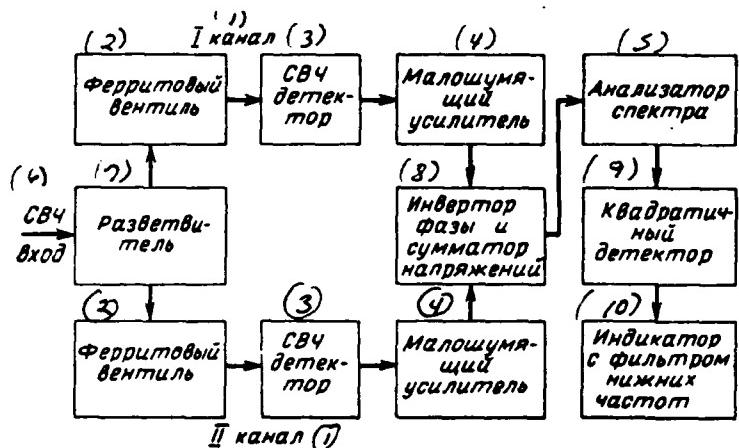
Fig. 2.20. Block diagram of two-channel (correlation) meter of fluctuations of amplitude, constructed according to principle of straight/direct detection.

Key: (1). Channel. (2). Ferrite valve/gate. (3). Detector. (4). low-noise amplifier. (5). Spectrum analyzer. (6). input. (7). Splitter. (8). Inverter of phase and summator of voltages/stresses. (9). Square law detector. (10). Indicator with low-pass filter.

Page 122.

The difference between these readings $\Delta = \overline{u_+^2(t)} - \overline{u_-^2(t)} = \overline{4u_a^2(t)}$ is proportional to the level of the unknown fluctuations of the amplitude of generator in the passband of the spectrum analyzer.

Thus, in two-channel measurements it is possible to clearly separate/liberate amplitude noise being investigated from noises of measuring channels. This makes it possible to confidently record the level of amplitude noise even then, when it is lower than the inherent noise level of meter. The minimally measurable level of amplitude

noise is limited, first of all, by the instability of
readings/indications indicator, by caused fluctuation in component of
the current of the detector of indicator.  The effect of this factor
on the accuracy of reading was dismantled above, in the examination of
the power-level indicator of the fluctuations of single-channel meter.
It is obvious that the confident reading of a difference in
readings/indications of indicator upon the total and differential
inclusions/connections is feasible only then, when the scatter of
readings/indications, caused by the instability of the current of
detector, is less than the measured difference.

Analysis shows that for recording power of amplitude noise, $\epsilon$
once of smaller power of inherent noise of meter (speech it goes about
power, given on input of amplifier of one of channels), it is
necessary to satisfy the condition: $\sqrt{\Delta F_c \tau_0} \gg \epsilon$, where $\Delta F_c$ - passband of
spectrum analyzer, and $\tau_0$ - time constant of integrating circuit (
RC-filter of indicator.  Thus, for example, with $\tau_0 = 1$ s and $\Delta F_c = 2$ kHz
$\epsilon_{\text{макс}} = 45$ (16.5 dB).

Since sensitivity of single-channel meter of fluctuations of
amplitude is limited by inherent noise level of meter, value
$\epsilon_{\text{макс}} = \sqrt{\Delta F_c \tau_0}$ shows, in how often more sensitive two-channel meter.  It
would seem, increasing the duration of measurement (i.e.  the time
constant of RC-filter), it is possible to unlimitedly raise the
sensitivity of two-channel meter.  However, this is not the case
Purely technical reasons, for example accuracy and stability of

balancing/trimming the inverter of phase are the limit of an
improvement in the sensitivity.  Ideal inverter must have the same
transmission factor upon the total and differential
inclusions/connections.  Actually transmission factor somewhat
changes, and this can give the different readings/indications of
indicator with the total and differential readings even in the absence
of coherent component in the channels, i.e., lead to the false result.
Obviously, this factor limits the minimally measurable level of
fluctuations.  Work experience with the correlation meters shows that
the maximum gain in the sensitivity in them in comparison with the
single-channel diagram does not exceed 25-30 dB.

In measurements at low frequencies advantages of two-channel
diagram decrease, since in this case passband of analyzer of spectrum
$\Delta F_c$ decreases, and considerable increase in time constant $\tau_0$ is
limited to need of guaranteeing operational stability of equipment for
time of measurement.

In practice sensitivity of two-channel meters of fluctuations of
amplitude, which use crystal of shf detectors, reaches values
$|\gamma_a(F)|_{\text{мин}} = -155$ dB at frequencies of fluctuations on the order of $10^3$
Hz and -170 dB at frequencies on the order of $10^5$ Hz.  During the use
of vacuum-tube diodes these numerals are improved by an order.

Let us note whereas that sensitivity of single-channel meter
could be of the same order, as two-channel, if there would be standard

not making noise of shf generator.  Then the process of measurements would be reduced to the alternating supply to identical power to shf detector from the investigated and standard generators.

Page 123.

In the first case of reading the indicator they would be proportional to the sum of the power of the amplitude noise of the generator being investigated and the inherent noise of meter, and secondly - power of the inherent noise of meter.  The difference between this of readings/indications would afford the possibility to determine the unknown level of amplitude noise.

During creation of two-channel meters problem of prevention of spurious coupling between channels, which is capable to lead to false correlation of their output voltages/stresses, appears.  The modulation high-frequency connection/communication between the crystal diodes is most dangerous.  The wave, reflected from the diode, is modulated by its noise.  Falling on the detector of another channel and being demodulated, this causes the appearance of voltage/stress, first channel coherent with the noise.  This process - mutual.  Calculations show that for preventing the ill effect of this connection/communication the decoupling between the detectors on shf signal must be not less than 35-40 dB.  It is provided by the bridge splitter of power and by ferrite valves/gates.

In Fig. 2.20 simplest version of two-channel meter was shown.  Is

more convenient, especially in the mass measurements, the version, the block diagram of low-frequency part of which is shown in Fig. 2.21. It differs from diagram in Fig. 2.20 in terms of use of automatic changeover sum - difference also in synchronous detector by output. The frequency of the changing over generator lies/rests below the spectrum of the fluctuations being investigated. in the presence of coherent component in the channels the intensity of noise output potential cf summator ( and consequently, and of the spectrum analyzer) periodically changes; the difference of the levels in the intervals of total and differential inclusions/connections is greater, the greater the level of coherent component. At the output of detector as a result of this the regular oscillation, whose frequency is determined by the frequency of the inversion of phase, appears, and amplitude - coherent signal level. This oscillation is cleaned of the harmonics and the part of the noise with narrow-band amplifier - filter; the measurement of its amplitude is made by the synchronous detector, the stability of readings/indications of which additionally increases with use of integrating RC-chain.
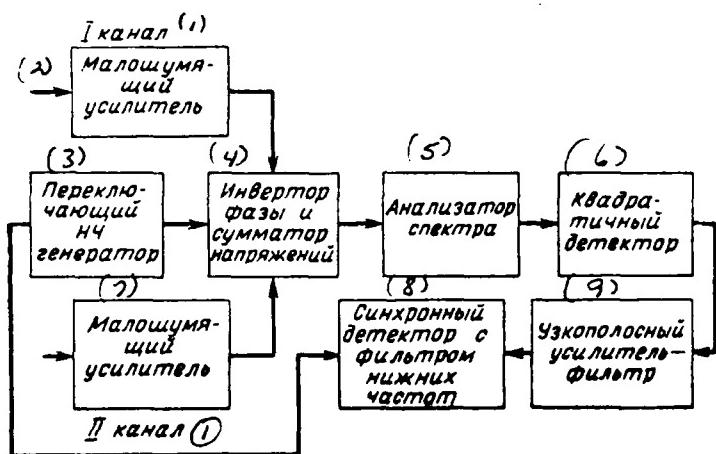
Fig. 2.21. Block diagram of two-channel meter of fluctuations of amplitude with automatic switching.

Key: (1). Channel. (2). Low-noise amplifier. (3). Changing over ... generator. (4). Inverter of phase and summator of voltages/stresses. (5). Spectrum analyzer. (6). Square law detector. (7). Low-noise amplifier. (8). Synchronous detector with low-pass filter. (9). Narrow-band amplifier - filter.

Page 124.

Questions, connected with two-channel measurement of fluctuations of amplitude are examined in [51-53]. In spite of greater (than in single-channel) complexity, two-channel meters found practical application because of the reliability of the results of measurements, and also because in a number of cases the levels of the fluctuations of amplitude are so/such low, which by other methods it is impossible to measure them.

Two-channel method can be useful and in measurement of frequency noises.  If the sensitivity of the single-channel measurements of the fluctuations of frequency is limited by inherent noise of measuring device, then transition/junction to the two-channel diagram gives straight/direct gain.  Can be encountered such case, when the levels of the fluctuations of the amplitude of generator itself and fluctuations of amplitude, converted from the fluctuations of frequency by discriminator, are compared.  Then two-channel meter can be used for exception/elimination or weakening of the effect of the fluctuations of amplitude on the result of measurement.  One of its channels is connected to the amplitude and the other to the FM discriminator.  If the amplification of channels is properly balanced, then deducting the voltages/stresses of channels, we are freed/released from the action of the fluctuations of amplitude.  The effectiveness of this method is limited to the inherent noise level of meter.

Finally, let us note that two-channel devices/equipment make it possible to measure correlation coefficient between fluctuations of oscillation of generator and low-frequency noise circuital currents of its electrodes.  Obtained thus information is useful for understanding of fluctuation processes in the generators.

2.3.  Superheterodyne methods of measuring the fluctuations.

It is known that sensitivity of superheterodyne receiver

considerably exceeds receiver sensitivity of straight amplification with reception of weak signals. This is connected with the fact that with the heterodyne method of reception/procedure the conversion loss of mixer are determined by the power of heterodyne and do not depend on the power of received signal.

In measurement of fluctuations we do not deal concerning weak, threshold signal. Problem consists not of reception/procedure and measurement of signal itself, but of recording of its weak modulation. Therefore a question about the sensitivity of the superheterodyne method of measuring the fluctuations should not be mixed with a question about the sensitivity with the reception of threshold shf signals.

Let us examine sensitivity of superheterodyne method of measurements of fluctuations of amplitude at first. The block diagram of measuring device is shown in Fig. 2.22. The oscillations of the generator being investigated are supplied to the mixer; there act the oscillations of heterodyne.
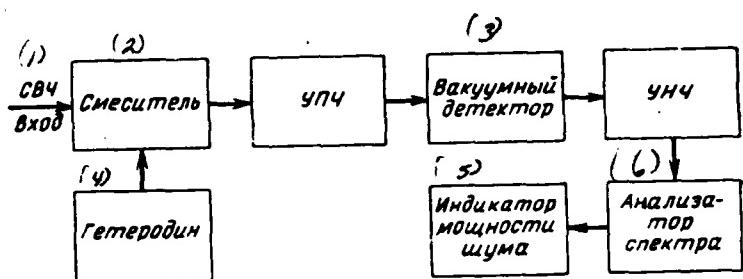
Fig. 2.22.   Block diagram of single-channel meter of fluctuations of amplitude, constructed according to superheterodyne principle.

Key:   (1).   shf input.   (2).   Mixer.   (3).   Vacuum detector.   (4). Heterodyne.   (5).   Power-level indicator of noise.   (6).   Spectrum analyzer.

Page 125.

After the mixing of the oscillation of difference frequency UPCh are amplified and are detected by vacuum diode.   Low-frequency envelope reproducing of the fluctuation of the amplitude of the oscillation of intermediate frequency, is amplified by the amplifier, whose band encompasses entire frequency band of the fluctuations in question, and it enters the spectrum analyzer.   The level of fluctuations is recorded by the power-level indicator of oscillations, in which is included the integrating filter.

We see that, beginning from second detector, laughter reproduces single-channel meter of straight/direct detection, to input of which, however, is supplied not oscillation of shf but oscillation, preliminarily converted to intermediate frequency. It is not difficult to ascertain that the transition/junction to the superheterodyne

principle cannot noticeably increase the sensitivity of the
measurement of the fluctuations of amplitude. Matter in the fact that
as the mixer of centimeter wave band we are forced to utilize entire
the same crystal diode.

It is theoretically shown and it is experimentally confirmed [46,
54, 55], that flicker noise of crystal diode effectively modulates
oscillation of intermediate frequency. This limits the sensitivity of
level measurements, close to that, which occurs in the meter,
constructed according to the diagrams of straight/direct detection.
Furthermore, in the superheterodyne circuit appears the supplementary
source of noise - heterodyne. The fluctuations of the amplitude of
the oscillation of heterodyne also are transferred to the intermediate
frequency and can mask the noise of the generator being investigated.
In spite of the fact that the second detector amplitude, the
fluctuations of the frequency of the generator being investigated and
heterodyne also can restrict sensitivity, since they completely are
transferred to the intermediate frequency.

With nonuniformity of amplitude-frequency characteristic of UPCh
noticeable effect of frequency detection, which leads to conversion of
fluctuations of frequency in fluctuation of amplitude, can appear. In
order to avoid this, it is necessary to make the passband of UPCh of
wide and to maximally equalize frequency characteristic in the center
section of the band. The effect of the noises of the second detector
is considerably weaker, since this detector vacuum, and it is possible

to consider that they do not limit the sensitivity of method.

Sensitivity of superheterodyne method of measuring fluctuations of amplitude it is possible to increase (just as method of straight/direct detection), after constructing meter according to correlation two-channel diagram (Fig. 2.23). The use of the independent heterodynes makes it possible to exclude them they are amplitude noises from the results of measurement [56].

In spite of considerable complication of diagram of superheterodyne measurements in comparison with diagram of straight/direct detection, in certain cases its use is expedient. The possibility of the investigation of fluctuations in the weak signals is a valuable quality of superheterodyne meter.

Fig. 2.24 shows curves of ultimate sensitivity of single-channel meters of superheterodyne and straight/direct detection. Data are acquired on one and the same copies of the crystal diodes, which served first as detectors in the diagram of straight/direct detection, then by mixers in the superheterodyne circuit. We see that on the high signal level the sensitivity of meters of both types is close. However, with the decrease of the power of the oscillation being investigated the sensitivity of the diagram of straight/direct detection rapidly falls, and it changes with superheterodyne little up to the power coefficients of order $10^{-3}-10^{-4}$ mW. Difference the behavior of diagrams is connected with the fact that the conversion

loss of mixer in the superheterodyne are determined by the power of heterodyne and do not depend on signal level.

Page 126.

During the straight/direct detection the conversion loss are determined signal level and rapidly increase with its decrease.

Thus, superheterodyne circuit makes it possible to investigate fluctuations of amplitude of very weak signals (to $10^{-4}$ mW) with very small loss of sensitivity. This is irreplaceable during the study of the fluctuations of low-power shf generators. The property indicated can be also used for an improvement in the sensitivity of the measurement of the fluctuations of frequency. At this question we now will pause [55, 57].

Above is indicated that with margin of power of generator being investigated sensitivity of measurement of fluctuations of frequency can be increased, using interference type frequency discriminator. Gain in the sensitivity is equal to the relation of power input and output of discriminator.
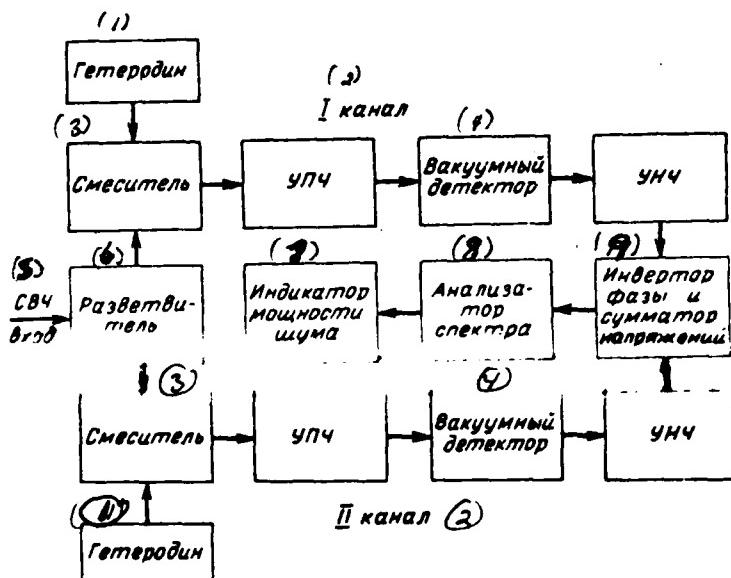
Fig. 2.23.                                    Fig. 2.24.

Fig. 2.23.  Block diagram of two-channel (correlation meter of

fluctuations of amplitude with independent heterodynes.

Key:  (1).  Heterodyne.  (2).  Channel.  (3).  Mixer.  (4).  Vacuum

detector.  (5).  shf input.  (6).  Splitter.  (7).  Power-level

indicator of noise.  (8).  Spectrum analyzer.  (9).  Inverter of phase

and summator of voltages/stresses.

Fig.  2.24.  Comparison of ultimate sensitivity of single-channel

meters of fluctuations of amplitude, constructed according to

superheterodyne circuit (1) and diagram of straight/direct detection

(2).  The power of heterodyne signal was 1 mW.

Key:  (1).  min.  (2).  mW.

Page 127.

If for recording the fluctuations of amplitude, converted by
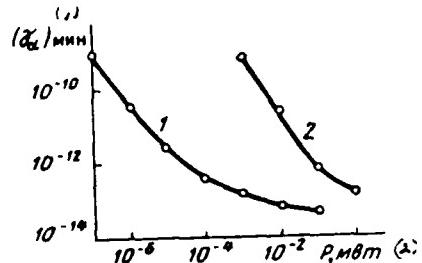
discriminator from the fluctuations of frequency, the meter,

constructed according to the diagram of straight/direct detection, is

used then the necessary degree of suppression by carrier is limited by

power on the order of 1 mW (as can be seen from Fig. 2.24); at the

smaller power the sensitivity sharply is fallen. The application of a

superheterodyne meter of fluctuations makes it possible to reduce this

power up to the value of order $10^{-3}$ mW, i.e., to increase the degree

of suppression of the carrier by approximately 3 orders. In so many

once increases the sensitivity of the measurement of the fluctuations

of frequency.

Block diagram of superheterodyne meter of such type is shown in

Fig. 2.25. Let us note that one of the factors, which limit the

sensitivity of this diagram, is the action of the fluctuations of the

amplitude of the generator being investigated and heterodyne.

However, there are procedures, with the aid of which it is possible to

overcome the limitation indicated. In practice it is possible to

realize the measurement of the fluctuations of the frequencies, whose

spectral density comprises $W_f(F) = 10^{-5} - 10^{-6}$ Hz$^2$/Hz at frequencies of

fluctuations $10^3 - 10^5$ Hz at the power of oscillation on the order of 1

mW being investigated. At greater power the sensitivity can be

respectively increased. Supplementary gain can be obtained during the

construction of meter according to correlation (two-channel) diagram.

In conclusion let us pause at possibility of applying

discriminator at intermediate frequency. This variant is inconvenient

fact that together with the fluctuations of the frequency of the generator being investigated occurs detection of the fluctuations of the frequency of heterodyne, which imposes extremely stringent requirements on the quality of the latter.  However, in certain cases its application is justified (for example, during the investigation of the very low-frequency fluctuations, when they are dangerous the vibration of the elements/cells of shf circuit).

2.4.  Measurement of spectral line width.

They are frequently interested in spectral line width of generator, caused not only by noises, but also in action of entire totality of disturbances/perturbations - both chaotic and regular (pulsation of feeding voltage/stress, ionic and mechanical oscillations).  During the calculation, carried out only taking into account noises, the strongly understated result can be obtained; whereas to consider the action of all enumerated factors is difficult.

DOC = 86049906
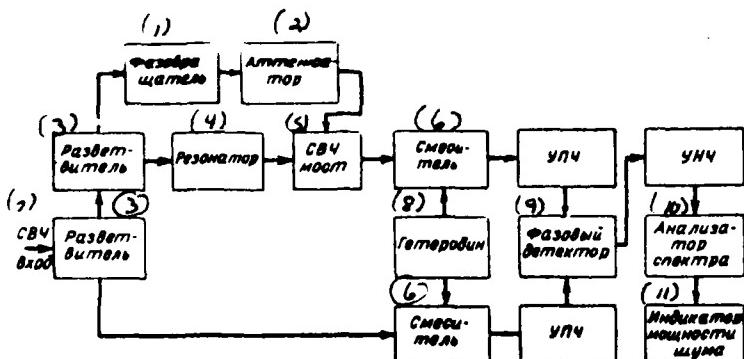


Fig. 2.25. Block diagram of a super heterodyne meter of frequency fluctuations with a frequency detector of the interference type. Key: (1). Phase shifter. (2). Attenuator. (3). Splitter. (4). Resonator. (5). shf bridge. (6). Mixer. (7). shf input. (8). Heterodyne. (9). Phase detector. (10). Spectrum analyzer. (11). Noise power indicator.

Page 128.

Therefore it is expedient to turn to the straight/direct experimental determination of spectral line width [55]. The block diagram of the installation, intended for this, it is shown in Fig. 2.26.

Oscillations of generator being investigated and heterodyne are supplied to mixer, then oscillations of intermediate frequency are amplified and are filtered by very narrow-band (quartz) filter. At

the output of filter the power-level indicator of oscillations is installed. With the retuning of the frequency of the heterodyne of reading/indication of indicator they must reproduce the form of the spectral duct/contour of the oscillation being investigated, provided the spectral line width of heterodyne and the filter pass band is sufficiently small on the comparison with the width of this duct/contour. For this the considerable complication of diagram (depending on the width of the line of the investigated generator) can be required. During the treatment of the results of measurement should be always considered the resolution of equipment.
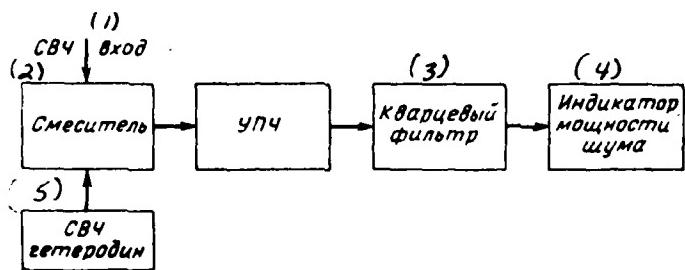
Fig. 2.26. Block diagram of meter of spectral width of line.

Key: (1). shf input. (2). Mixer. (3). Quartz filter. (4). Power-level indicator of noise. (5). shf heterodyne.

Page 129.

Chapter 3.


Requirements, presented to by klystron oscillator in the radar

devices/equipment.

1. Requirements, presented to reflex klystrons, utilized as

heterodynes of pulse radar.


Maximum radar detection range of target is one of most important

tactical parameters of radar. It depends on the power of transmitter,

antenna gain, size/dimension of target and sensitivity of the receiver

of radar. In the constant/invariable parameters of transmitter and

antenna maximum working range is greater, the greater the sensitivity

of receiver. This dependence can be represented in the form [58]:

$$R_{макс} = \frac{A}{P_{пор}^{1/4}},\qquad(3.1)$$

where A - coefficient, depending on the power of transmitter, antenna

gains and size/dimension of echoing area of target; $P_{пор}$ - power of

the threshold signal, detected by radar.


In turn, value $P_{пор}$ is connected in a direct manner with

sensitivity of receiver, which is limited to noise level. The noise

reduction in the input cascades/stages of receiver makes it possible

to lower the power of threshold signal and to increase outer detection

limit thereby.

Superheterodyne type receivers found widest acceptance in contemporary radars. The block diagram of this receiver is depicted in Fig. 3.1. As the local oscillator, as a rule reflex klystrons are used.

Signal echo from target comes to input of high-frequency amplifier.

Page 130.

After preliminary amplification it falls on the semiconductor mixer, where the oscillations of the difference frequency between the echo signal and the signal of the local oscillator are isolated. After final amplification in the IF amplifier and second detection the video signal enters the display unit.

Requirement of minimum inherent noise level, which appear in receiver, is one of fundamental requirements for radar receiver. If as the first cascade/stage of receiver is utilized high-frequency amplifier ( LBV, parametric amplifier, etc.), then the noise level of receiver as a whole virtually is determined by this cascade/stage. When high-frequency amplifier is absent and the echo signal directly enters the semiconductor mixer, the noise level of receiver in essence depends on the inherent noise of semiconductor diode and noises of heterodyne at the intermediate frequency. The noises of heterodyne in the sidebands, distant behind the intermediate frequency of receiver carrier to the value, mixing with it, create the noise spectrum at the

intermediate frequency in the band of receiver. Since mixing of arrays is sensitive to changes in the signal amplitude ( but not frequency), then the amplitude noise of heterodyne play the determining role.

Noise factor serves as measure of noise, which appears in receiver. Factor of noise $K_{\text{ш}}$ is defined as

$$K_{\text{ш}} = \frac{P_{\text{вх}}/P_{\text{ш вх}}}{P_{\text{вых}}/P_{\text{ш вых}}}, \qquad (3.2)$$

where $P_{\text{вх}}$ - power of input useful signal; $P_{\text{ш вх}}$ - power of input noise; $P_{\text{вых}}$ - power of output signal; $P_{\text{ш вых}}$ - power of output noise.

(1)

CBЧ Вход

(2)

| Смеситель | → | УПЧ | → | Второй детектор (3) | → | Видео-усилитель (4) | → К индика- тору ( 5). |

(6)

| CBЧ гетеродин |
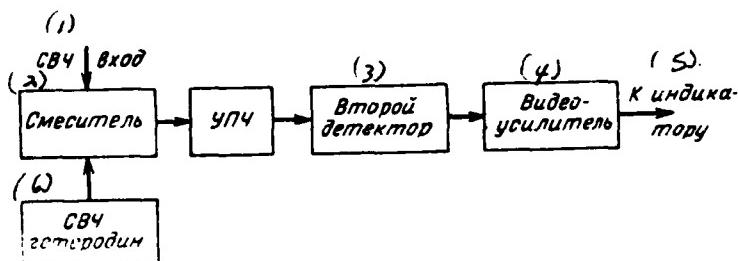
Fig. 3.1.  Block diagram of heterodyne of shf receiver.

Key:  (1).  shf input.  (2).  Mixer.  (3).  Second detector.  (4).

Video amplifier.  (5).  To indicator.  (6).  shf heterodyne.

Page 131.

It is possible to obtain another expression for $K_\text{ш}$, keeping in mind, that power of input thermal noise with agreement of receiver on input

$$P_\text{ш вх} = k T_0 \Delta f,\qquad(3.3)$$

where $T_0$ - absolute inlet temperature of receiver; k - Boltzmann constant; $\Delta f$ - band of receiver.  Then

$$K_\text{ш} = \frac{P_\text{ш вых}}{k T_0 \Delta f K},\qquad(3.4)$$

where  $K = \dfrac{P_\text{вых}}{P_\text{вх}}$ - factor of amplification of receiver.

If we designate power of supplementary noise, which appears in receiver, through $\Delta P_\text{ш}$, i.e.

$$P_\text{ш вых} = k T_0 \Delta f K + \Delta P_\text{ш},\qquad(3.5)$$

then

$$K_\text{ш} = 1 + \frac{\Delta P_\text{ш}}{k T_0 \Delta f K}.\qquad(3.6)$$

Thus, for "ideal" receiver, which does not create supplementary noise $(\Delta P_{\text{ш}}=0)$, $K_{\text{ш}}=1$. Expressions (3.2), (3.4) and (3.6) for the factor of the noise of receiver are equivalent to each other. For standardization $K_{\text{ш}}$ it is customary to assume $T_0=290°K$. In this case value $kT_0=4\cdot10^{-21}$ w/Hz.

If receiver consists of two series-connected cascades/stages, each of which is characterized by their factor of noise $K_{\text{ш1}}$ and $K_{\text{ш2}}$, then coefficient of receiver noise as a whole

$$K_{\text{ш}} = K_{\text{ш1}} + \frac{K_{\text{ш2}} - 1}{K_1}, \qquad (3.7)$$

where $K_1$ - factor of amplification of first cascade/stage.

Frequently noise factor is expressed in decibels

$$(K_{\text{ш}})_{\text{дб}} = 10\lg K_{\text{ш}}. \qquad (3.8)$$

For receivers from low by noise factor they use also concept of effective noise temperature $(T_{\text{ш}})$ at input of receiver, which creates at its output noise $\Delta P_{\text{ш}}$

$$\Delta P_{\text{ш}} = kT_{\text{ш}}\Delta f K. \qquad (3.9)$$

Then expression (3.6) takes the form

$$K_{\text{ш}} = 1 + \frac{T_{\text{ш}}}{T_0}. \qquad (3.10)$$

Page 132.

Supplementary noise, which appears in superheterodyne receiver, is consequence of noises of mixer, heterodyne and IF amplifier. The factor of the noise of this receiver $(K_{\text{ш 0}})$ taking into account the

noises only of mixer and amplifier in accordance with expression (3.7)

$$K_{\text{ш 0}} = K_{\text{ш c}} + \frac{K_{\text{ш y}} - 1}{K_c} , \qquad (3.11)$$

where $K_{\text{шc}}$ - factor of the noise of mixer; $K_{\text{шy}}$ - factor of the noise of amplifier; $K_c$ - transmission factor of mixer, equal to $1/L_c$ ($L_c$ - the conversion loss of mixer diode).

After introducing concept of relative temperature of noise of mixer $t_c$, equal to relation power of noises of mixer at intermediate frequency to power of noise of located at standard temperature effective resistance

$$t_c = \frac{K_{\text{ш c}} k T_0 \Delta f K_c}{k T_0 \Delta f} = \frac{K_{\text{ш c}}}{L_c} , \qquad (3.12)$$

we will obtain final expression for coefficient of receiver noise taking into account noises of semiconductor mixer and IF amplifier:

$$K_{\text{ш 0}} = L_c (t_c + K_{\text{ш y}} - 1). \qquad (3.13)$$

Noises of heterodyne cause increase in factor of noise of real receiver, creating supplementary relative temperature of mixer $(t_r)$:

$$K_{\text{ш}} = L_c (t_c + t_r + K_{\text{ш y}} - 1) \qquad (3.14)$$

or

$$K_{\text{ш}} = K_{\text{ш 0}} \left( 1 + \frac{t_r}{t_c + K_{\text{ш y}} - 1} \right) . \qquad (3.15)$$

Thus, additional increase in coefficient of receiver noise due to noises of heterodyne in decibels will be

$$\Phi = \frac{K_{\text{ш}}}{K_{\text{ш 0}}} = 10 \lg \left( 1 + \frac{t_r}{t_c + K_{\text{ш y}} - 1} \right) . \qquad (3.16)$$

For real radar receivers of centimeter band, where as heterodynes

use reflection klystrons, increase of noise factor can be several decibel.

Page 133.

Actually, if we consider that ratio of power of amplitude noises of klystron at intermediate frequency in band 1 Hz to carrier output $\gamma_a = 5 \cdot 10^{-17}$ [2], then supplementary relative temperature of mixer due to noises of heterodyne $(t_r)$ with that supplied to mixer of power of heterodyne $P_r = 10^{-3}$ W will be

$$t_r = \frac{P_{\text{wr}}}{kT_0 \Delta f} = \frac{\gamma_a P_r \Delta f}{kT_0 \Delta f} = \frac{\gamma_a P_r}{kT_0} \approx 12$$

$(P_{\text{wr}}$ — power of noises of heterodyne in band UPCh). The power of the noises of heterodyne in one sideband is here taken into consideration. Assuming/setting $t_c = 3$ and $K_{\text{wy}} = 3$. from expression (3.16) we will obtain that $\Phi \approx 4$ dB.

For reduction in receiver noise special methods of noise suppression of heterodyne are used. Thus, between the heterodyne and the mixer sometimes is switched on the narrow-band filter, tuned to a frequency of the heterodyne, the passband of which is considerably less than the intermediate frequency of receiver. In this case lateral noise components of heterodyne do not fall on mixer. However, this method possesses a number of the deficiencies/lacks, basic from which is the complexity of the retuning of operating frequency. For changing the frequency is necessary the adjustment of not only reflex klystron, but also synchronous retuning of the cavity resonator, which is narrow-band filter.

Balancing network of mixer, which makes it possible to sharply decrease ill effect of noises of heterodyne, more extensively is used. The operating principle of balance mixer is clarified Fig. 3.2. The signal of heterodyne is supplied into arm H of twin T-piece. With the symmetry of lateral arms this signal is divided between them equally and in one and the same phase enters mixer diodes. The echo signal adopted is supplied into arm E of twin T-piece and, in view of the known properties of dual waveguide tee, enters two mixer diodes with the phase shift between them on 180°.
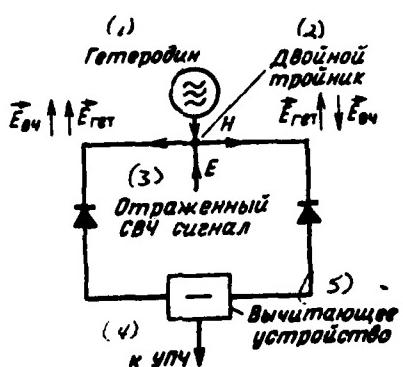
Fig. 3.2. Diagram of balance mixer.

Key: (1). Heterodyne. (2). Twin T-piece. (3). Echo ... signal. (5). Subtractor. (4). to:.

Page 134.

On subtractor cophasal noise signals of heterodyne will be deducted, and useful signals of intermediate frequency, shifted between themselves on phase on 180°, — store/add up. This mixer provides the essential noise suppression of heterodyne (to 20 dB) [59], retaining in this case broad-band character and reliability in operation. Supplementary relative temperature at the use of a balance mixer will be equal to

$$t_{\text{г бал}} = \frac{t_{\text{г}}}{d_{\text{бал}}} , \qquad (3.17)$$

where $d_{\text{бал}}$ - value of noise reduction of heterodyne in the balance mixer. With $d_{\text{бал}} > 10$ dB the noises of real reflex klystrons virtually do not affect the total noise level of receiver

2. Requirements, presented to by klystron oscillator in the coherent radar systems.

Usual radars, which use pulse-modulated signal, make it possible
to obtain information about target coordinates:  for range - on
temporary displacement between sounding and echo pulses, angular
coordinates - on antenna directivity at moment of reception of echo
from target signal.  Under the typical conditions for the work of
radar the principal ray of the narrow-beam antenna illuminates not
only target, but also part of the earth's surface and artificial
reflectors, if they are used for the creation of interferences.

Under these conditions there appears one of essential
deficiencies/lacks in usual radars, which consists in complexity of
detection of moving/driving targets in presence of reflected from
motionless ground features or artificial passive reflectors, which
create interfering background on scope.  The difficulty of
sufficiently precise determination of the speed of moving object is
another serious deficiency/lack in usual radar.

Of deficiencies/lacks indicated are to a considerable extent
deprived radars, in which are used coherent methods of
isolation/liberation of moving/driving targets against the background
of reflections from stationary targets, based on use of Doppler
effect.  Such methods are realized both in the radars with the
continuous radiation/emission and in pulse radar.

Page 135.

Essence of coherent methods of detection of moving/driving targets consists in the fact that frequency bias/displacement to allowance of Doppler undergoes signal echo from moving/driving target:

$$F_{A} == \frac{2v_{r}}{\lambda} , \qquad (3.18)$$

where $v_{r}$ - radial velocity of target (i.e. target speed relative to radar); $\lambda$ - wavelength of radar signal.

Signals of this bias/displacement echo from stationary targets are not obtained. A comparison of coherent supporting/reference oscillations [1], transmitter and signal reflected from the target in the frequency (or phase) makes it possible to obtain information about the parameters of the motion of moving object.

FOOTNOTE [1]. Oscillations are called coherent, if in the period of observation between them a constant/invariable phase difference is retained. ENDFOOTNOTE.

In such radars, in principle, limitations, connected with detection of moving/driving targets against the background of reflections from stationary targets, characteristic for usual sampled-data systems, are absent, since for separation of signals, reflected from moving/driving and stationary targets, Doppler frequency shift is utilized.

According to form of sounding signal and using methods of comparison of parameters of echo and reference signals radar systems,

which realize detection of moving/driving targets, can be broken into two groups:   system of continuous and quasi-continuous [2] radiation/emission and sampled-data systems with selection of moving/driving targets ( SDTs).

FOOTNOTE [2].   In the systems of quasi-continuous radiation/emission is utilized pulse signal with the high repetition frequency (ten - hundreds of kilohertz) and low duty cycle (<10).   ENDFOOTNOTE.

In the radars of continuous and quasi-continuous radiation/emission reference signal is the part of the power, selected/taken from the master oscillator, which works in the continuous duty.  In pulse radar with SDTs reference signal, as a rule is formed/shaped via the phase synchronization of the oscillations of the high-frequency oscillator, which works in the pulsed operation, with the oscillations of the special coherent heterodyne, which works in the continuous duty.  Thus the signal of this heterodyne can be utilized as supporting/reference with the reception of the echo signals, which relate to this sounding pulse.  Thus, in the stations of this type coherence is retained only in the limits of one repetition period and, strictly speaking, such radars are not truly coherent.

Page 136.

     Coherent methods of isolation/liberation of moving/driving targets find wide application in radar systems, fundamental designation/purpose of which is detection of moving/driving targets

against the background of strong interferences from ground features
(for example, detection of low-flying aircraft or aircraft against the
background of earth's surface) and precision determination of speed of
motion of these targets.  The parameters of radars, which realize
isolation/liberation and detection of the moving/driving targets -
their interference shielding, ultimate sensitivity (range), accuracy
of the measurement of the parameters of the motion of target - are
limited by the fluctuations of the signals, reflected from the ground
features, by the fluctuations, caused by the displacement/movement of
directional characteristic of antenna with the survey/coverage, and
also by instabilities in the work of the separate nodes of radar.  All
enumerated fluctuations and instabilities lead to the onset of the
"parasitic" amplitude, frequency and phase modulation of signals,
reflected from the motionless objects/subjects with their passage
through receiving circuit.

For shf instruments most difficultly feasible are requirements on
operational stability, presented to master oscillators and
heterodynes, as which extensively are used klystron oscillators of
small power.  In this case the specificity of the advanced
requirements for such generators significantly depends on the specific
designation/purpose of radar.

Will be examined below fundamental requirements for master
oscillators and heterodynes, in connection with their use in radars of
continuous and pulse radiation/emission.  The special features of

operation of themselves radars will be touched upon only inasmuch as, since this is necessary for the best understanding of the requirements, presented to the generators of shf.

Are more full of information about work of radar systems, which realize detection of moving/driving targets, it is possible to stress in specialized literature [58, 60].

2.1.  Requirements, presented to the master oscillators (heterodynes) in the continuous-wave radars.

Simplified block diagram of typical, continuous-wave radar, intended for detection of moving/driving targets and determination of speed of their motion, is given in Fig.  3.3.  The angular coordinates of target can be obtained on the directivity of antenna system at the moment of reception.

Page 137.

Given diagram of radar does not provide ranging to target.  This is possible, however, by the complication of the schematic of radar, for example due to the use of a two-frequency signal or introduction to special modulation of the sounding signal.

Transmitter, which consists of master oscillator (for example, on reflex klystron), amplifier-convertor, in which simultaneously is realized frequency shift to value of intermediate frequency $f_{np}$, and

terminal amplifier, continuous monochromatic oscillation [1]

$$U_1(t) = U_1 \cos(\omega_0 t + \varphi_0) \qquad (3.19)$$

emits

FOOTNOTE [1].  The below explanation of the principle of the operation
of radar of continuous radiation/emission at first is given under the
assumption that the fluctuations of oscillation, caused by noise
effect in the vacuum-tube instruments, are absent.  ENDFOOTNOTE.

The signal

$$U_2(t) = U_2 \cos[\omega_0(t - t_u) + \varphi_0] \qquad (3.20)$$

echo from the target enters to the mixer.  This signal has the changed
phase due to the time lag to the period of propagation to the target
and vice versa $(t_u = 2R/c$, where R - distance of the target, c - velocity
of propagation of electromagnetic vibrations), i.e.

$$U_2(t) = U_2 \cos\left(\omega_0 t - \frac{2R\,\omega_0}{c} + \varphi_0\right). \qquad (3.21)$$
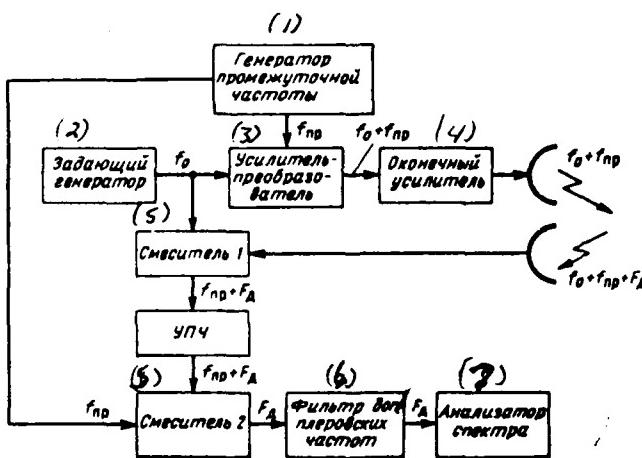
Fig. 3.3.   Block diagram continuous-wave radar.

Key:   (1).   Generator of intermediate frequency.   (2).   Master

oscillator.   (3).   amplifier-transformer.   (4).   Terminal amplifier.

(5).   Mixer.   (6).   Doppler filter.   (7).   Spectrum analyzer.

For stationary target R=const, for target, which moves towards station,

$$R = R_0 - v_r t, \qquad (3.22)$$

where $R_0$ - initial detection range of target; $v_r$ - radial velocity of target. In this case echo signal (3.21) will be

$$U_2(t) = U_2 \cos\left(\omega_0 t - \frac{2R_0 \omega_0}{c} + \frac{2v_r}{c}\omega_0 t + \varphi_0\right). \qquad (3.23)$$

Keeping in mind, that

$$\frac{2v_r}{c}\omega_0 = 2\pi F_{\text{д}} = \Omega_{\text{д}},$$

we will obtain

$$U_2(t) = U_2 \cos\left[(\omega_0 + \Omega_{\text{д}})t - \varphi_{\text{и}0} + \varphi_0\right], \qquad (3.24)$$

where $\varphi_{\text{и}0} = R_0 \omega_0 / c.$ Thus, the adopted from the moving/driving target signal has frequency bias/displacement to value $\Omega_{\text{д}}$ of the correction of Doppler.

After conversion in receiving circuit echo signal enters Doppler filter. The band of filter is determined by the relationship/ratio

$$\Delta F = F_{\text{д макс}} - F_{\text{д мин}} = \frac{2f_0}{c}(v_{r \text{ макс}} - v_{r \text{ мин}}), \qquad (3.25)$$

where $v_{r \text{ макс}}$ and $v_{r \text{ мин}}$ - with respect maximum and minimum radial target speeds, determined by radar. Therefore through the filter only differential combination component of the spectrum of the signal, which is formed after detection $(F_{\text{д}})$ passes. The signals from the motionless objects/subjects, which do not have Doppler effect, through the filter will not pass. Depending on the designation/purpose of station and mode of its operation (speed of the detected objects, the

frequency of transmitter) the region of Doppler frequencies can encompass range from ten hertz to several hundred kilohertz.

Spectrum analyzer encompasses tunable narrow-band filter, which realizes search in frequency in band of expected Doppler frequencies and lockon after detection.  In this way the spectrum analyzer makes it possible to isolate and to determine the amount of Doppler frequency switch, proportional to target speed relative to radar.

Page 139.

Fig. 3.4 depicts real situation, which occurs with target detection.  Into the receiver of radar enters not only the signal, reflected from the moving/driving target and having because of this, Doppler frequency shift, but also signals, reflected from the local motionless objects/subjects, and the part of the power of transmitter, which leaks into the receiving antenna.  Under such conditions works the fundamental technical characteristics of radar are following [61, 62]:

- quality of the selection of the signals, reflected from the moving/driving targets, i.e., the visibility of target against the background of powerful/thick reflections from the stationary targets (natural and artificial);

- sensitivity on the reception of the echo signals with Doppler frequency shift, which determines the minimal size of the targets detected and the range of their detection;

- resolution on the speed of the motion of target, and also the

accuracy of its determination.

Let us examine in more detail limitation, which superimpose instabilities of oscillations/vibrations of master oscillator and heterodyne of characteristics of radar [1] indicated.

FOOTNOTE [1].   In this case we will assume that the noises of amplifier stages of transmitter the insignificant in comparison with the noises of the master oscillator, and signals of the master oscillator and heterodyne (in contrast to the block diagram, given in Fig. 3.3.) they are created by different klystron oscillators.   ENDFOOTNOTE.

The sounding oscillations/vibrations of transmitter due to the effect of the noises of the master oscillator are not monochromatic.   Because of this, the powerful/thick echo signal from the adjacent objects will have noise sidebands.
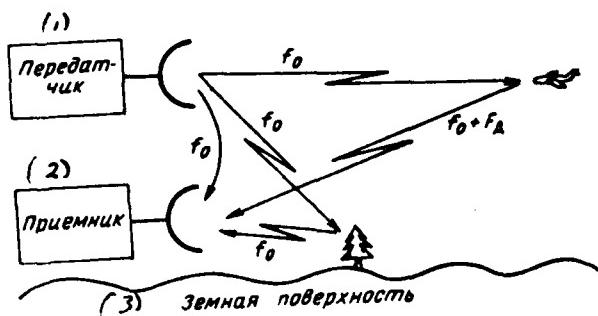
Fig. 3.4.  Diagram of signals, which enter receiver radar in real situation.

Key:  (1).  Transmitter.  (2).  Receiver.  (3).  Earth's surface.

Page 140.

Noise components in the Doppler frequency band bears the signal, which leaks from the transmitting antenna into the receiving.

The same effect as noises of transmitter, they will produce fluctuations of oscillation/vibration of heterodyne, which have noise components at Doppler frequencies.

Effect of noise sidebands of transmitter and heterodyne on visibility of target against the background of interfering reflections is shown in Fig.  3.5.  As it follows from the figure, the visibility of target is limited by the noise level at the Doppler frequencies in the signals, reflected from the motionless objects/subjects, noise components in the signal of transmitter, which directly leaks into the receiving antenna, and by the noises of heterodyne.  For guaranteeing the target assigned to visibility the noise level of the master

oscillator and heterodyne in the Doppler frequency band interesting
must not exceed the specific value.

The sensitivity of system on reception of echo signals with
Doppler frequency shift is directly connected with spectral line width
of signal echo from target.  During the supplying to the filter of the
analyzer of spectrum of narrow-band signal and broadband noise,
fundamental source of which are noise components in the
oscillations/vibrations of transmitter and heterodyne, an increase in
the ratio of the power of signal to the power of noise (signal/noise)
at its output and, consequently, an improvement in the sensitivity of
system will occur until the filter pass band becomes equal to width of
the line of the echo signal .  Further contraction of the band of
filter will not lead to an improvement in this relation, since
together with the decrease of energy of noises will occur the decrease
of energy of the echo signal.  Thus, the width of the line of the echo
signal directly determines receiver sensitivity:  the narrower the
spectral line, the weaker the signal can be recorded by receiver.
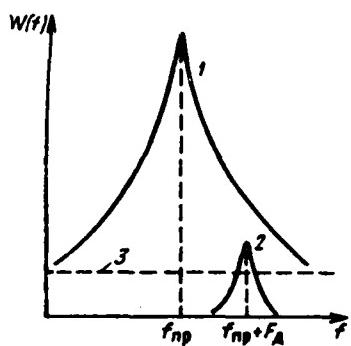
Fig. 3.5.   Amplitude-frequency relationships/ratios for the radar taking into account noise sidebands:   1 - sidebands of signal of transmitter, which leaks into receiving antenna; noise components of oscillations/vibrations of heterodyne; interfering reflections taking into account noises of transmitter; 2 - echo from target signal; 3 - inherent noise level of receiver.

Page 141.

Thus can be provided the detection of finer/smaller targets at the larger range.

The spectral line width of echo signal is determined in essence by width of line of master oscillator, although expansion of line phase instabilities in amplifier chain/network of transmitter, fluctuation of echo signal due to vibration of echoing area of target, irregular motion of target, scanning of ray/beam of antenna, etc affect also.

Thus, sensitivity of system and visibility of moving/driving

targets against the background of interfering reflections are
determined by three fundamental factors:

- by fluctuations of signal, reflected from target, that
determine width of its spectral line;

- by fluctuations of signals, reflected from stationary targets;

- by fluctuations of signal of transmitter, which leaks into
receiving antenna.


Latter/last two factors determine level of broadband noise at
input of receiver in they are connected with presence of noise
sidebands of master oscillator, falling into region Doppler
frequencies.  Let us rate/estimate the acceptable noise level of the
master oscillator with the assigned sensitivity of system.  This level
is determined by the band of filter, by the power of transmitter and
by decoupling between the transmitting and receiving antennas taking
into account reflections from the adjacent motionless local objects.


with band of filter 1000 Hz, of receiver sensitivity to this band
$10^{-16}$ W, power of transmitter 1 kW and decoupling between antennas
(taking into account reflections from adjacent stationary targets) of
90 dB ratio of power of frequency noise to average/mean power of
transmitter (master oscillator) must be  $\eta < -130$ dB/Hz, since
realization of maximum sensitivity of receiver [1] is only in this case
possible.


FOOTNOTE [1].  Actually, into the receiver it will pass the part of the

power of transmitter P=10³·10⁻⁹ $W$=10⁻⁶ W.  For using the maximum

receiver sensitivity 10⁻¹⁴ W in the band 1000 Hz $\gamma$, it must not exceed

10⁻¹³ 1/Hz (-130 dB/Hz).  ENDFOOTNOTE.

In practice the required relation, for example for airborne RLS, is

-110 dB/Hz [63].  In other cases it can be substantially harder.

Values  $\gamma$ (-110 indicated and - 130 dB/Hz) correspond (at

frequency F=5 kHz) to spectral density of frequency fluctuations

5·10⁻⁴ and 5·10⁻  Hz²/Hz and they cannot be provided without

application of special measures for noise reduction (S 4; S 5 Chapter

4).

In given example it was assumed that functions of master

oscillator and heterodyne are realized by different instruments.

Page 142.

If for shaping of the signal of transmitter and heterodyne one and the

same generator (Fig. 3.3) is utilized, then between these

oscillations/vibrations there is a correlation, which decreases

requirements for their stability.  The permissible decrease of

signal-to-noise ratio for the master oscillator in this case is

connected with the delay time of signal in the channels of RLS (for

the signal, which directly leaks into the receiving antenna) and with

the time of the emission of the signal to the reflecting stationary

target and vice versa.  Supplementary gain due to correlation [62]:

$$\mu = \frac{1}{\left(2 \sin \frac{\Omega_{\text{я}} \tau}{2}\right)^2} \approx \frac{1}{(\Omega_{\text{я}} \tau)^2}, \qquad (3.26)$$

where $\Omega_{\text{я}}$ – angular frequency of "parasitic" modulation; $\tau$ – delay time. For example, at the frequency of 10 kHz with $\tau = 10^{-4}$ s

$$\mu = 2.5 \cdot 10^2 \text{ (24 dB)}.$$

Spectral line width of echo signal determines not only ultimate sensitivity of radar system, but also its resolution on target speed. The possibility of the discrimination of two targets, which move with the different, but close speeds, is determined by the band of Doppler narrow-band filter. Since a difference in the speeds is proportional to the difference in the accompanying Doppler frequency shifts, the decrease of the band of filter increases the resolution of system in the speed. In this case the possible resolution, i.e. minimum width of band of filter, is determined by the spectral line width of the signal echo from the target.

For radars, intended for detection of aircraft against the background of reflections from ground-based objects/subjects, requirement for resolution on speed is 8-15 m/s, which corresponds to width of line of echo signal 1000-500 Hz in work of transmitter in three-centimeter wavelength range [63.

In practical cases spectral line width of echo signal, caused by noisiness of klystron oscillators, does not set substantial limitations on sensitivity and resolution RLS, since hertz (S 1 Chapter 2) is of the order ten.

Page 143.

Noise side components of oscillation spectrum of master oscillator and heterodyne, arranged/located sufficiently close to medium frequencies of these oscillations/vibrations, generally speaking, are also source of absolute error in determination of target speed and range to it.  However, requirements for the quality of the spectrum of the signal of the master oscillator (heterodyne) from this point of view, as a rule are not determining, since greater error in the determination of the speed and range introduces the low- frequency fluctuations of the echo signal, caused by other mentioned earlier already reasons, not connected with the work of the generators of shf [62, 64].

For reliable work of radar of important is one additional characteristic of oscillation spectrum of master oscillator and heterodyne - absence in noise spectrum of components due to regular frequency or phase modulation in band of Doppler filter, which exceed noise level.  These components in the frequency noise spectrum (S 4 Chapter  1) can be accepted as the signal, reflected from the target, which will lead to the capture   "decoy" with the realization of search.

Given above requirements for by master oscillator and to heterodynes of radar systems of continuous radiation/emission virtually completely are propagated also to quasi-continuous radars, since interfering reflections from adjacent stationary targets come in

the same intervals of time, that also reflection from moving/driving targets.

In conclusion one should say that actual requirements for acceptable noise level of generators of shf in continuous-wave radars cannot be formulated without taking into account designation/purpose of and connected with this diagram of its construction and required technical characteristics, i.e., by range of target speeds interesting and by permissible, in connection with this, range of their detection, by conditions for arrangement/position of etc. However, it is obvious that if necessary for the detection of the relatively slowly moving/driving targets the determining role play the noises in the low-frequency part of the Doppler range, with the rapidly moving targets - in the more high-frequency part. At the same time in the first case, generally speaking, the smaller sensitivity of system (i.e. the large noises of the generators of shf/SVCh) is permitted, since the time of the motion of target to RLS can remain sufficient for making of the corresponding decisions.

Page 144.

2.2. Requirements, presented to the heterodynes in coherent-pulse radars with the SDTs.

Use of Doppler effect in radars of pulse radiation/emission, just as in systems of continuous radiation/emission, it makes it possible to isolate moving/driving targets against the background of

reflections from stationary targets.  The widest acceptance received the coherent-pulse stations, in which the signal echo from the target is compared with reference oscillations of the special generator, called coherent.  The simplified block diagram of such the coherent-pulse radar is given in Fig. 3.6.

High-frequency oscillator (for example, magnetron) emits high-frequency pulses with specific duration and repetition frequency. Reference voltage is created by the coherent heterodyne, which is the high-stability generator of intermediate frequency.  Use as reference oscillations of the signal of high-frequency oscillator is eliminated, since it operates on a pulsed basis.

Synchronization of phase of signal of coherent heterodyne with phase of sounding radio pulse of high-frequency oscillator (transmitter) is realized as follows.  The part of the power of the pulse sounding signal is converted in mixer 1 into the signal of intermediate frequency, whose phase is determined by the phase of the oscillations/vibrations of transmitter.
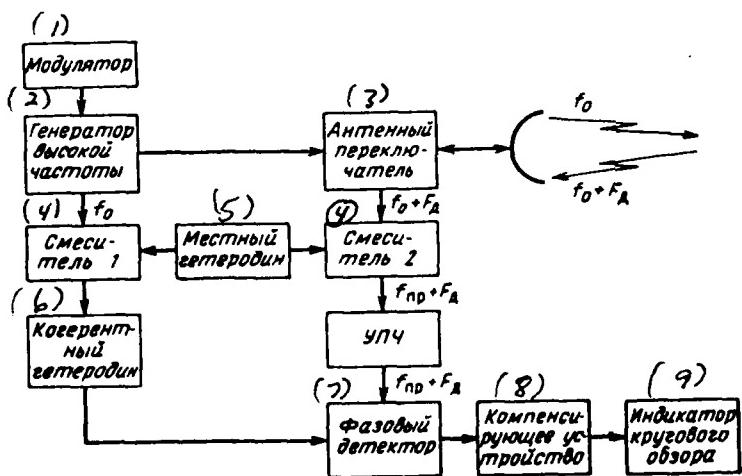
Fig. 3.6.   Block diagram of pulse-modulated RLS with SDU.

Key:  (1).  Modulator.  (2).  High-frequency oscillator.  (3).

Antenna switch.  (4).  Mixer.  (5).  Local heterodyne. (6).  Coherent

heterodyne.  (7).  Phase discriminator.  (8).  Compensator.  (9).

Plan position indicator.

Page 145.

The formed pulse of intermediate frequency is supplied to the coherent

heterodyne, synchronizing the phase of its continuous oscillations

with the phase of the reference pulse of intermediate frequency.

Thus, an output signal of coherent heterodyne can be utilized as the

supporting/reference with the reception of the echo signals, which

relate to this sounding pulse of transmitter.

Echo from target signal, converted in mixer 2 into signal of

intermediate frequency, comes after UPCh phase discriminator, to which

also is supplied reference signal from coherent heterodyne.  The

pulses reflected from the motionless objects/subjects, come in each repetition period with the completely specific phase shift with respect to the sounding pulse of transmitter. The pulses reflected from the moving/driving targets, have supplementary Doppler phase shift from one period to the next, which is determined by the expression

$$\Delta\varphi = \Omega_{\text{л}} T_{\text{п}}, \tag{3.27}$$

where $\Omega_{\text{л}}$ - angular Doppler frequency, determined by relative target speed; $T_{\text{п}}$ - repetition period.

After detection output signal can be recorded in the following form:

$$u_{\text{вых}} = U_{\text{пых}}(1 + m \cos\varphi), \tag{3.28}$$

where $\varphi = \varphi_{\text{п0}} = 2R\omega_0/c = \text{const}$ - for signals, reflected from stationary targets, and $\varphi = \varphi_n = \varphi_{n-1} + \Delta\varphi = \varphi_{n-1} + \Omega_{\text{л}}(n-1)T_{\text{п}}$ - for signals, reflected from moving/driving targets (n - number of repetition period).

Thus, after detection signals from stationary targets will be sequence of pulses of constant amplitude, and signals from moving/driving targets - sequence of pulses modulated in amplitude with Doppler frequency of

$$u_{\text{вых}} = U_{\text{вых}}[1 + m \cos\Omega_{\text{л}}(n-1)T_{\text{п}}]. \tag{3.29}$$

For selection of pulses modulated in amplitude from moving/driving target compensators, which make it possible to suppress and to remove signals from motionless objects/subjects are utilized

from scope. One of such devices/equipment is the system of
cross-period compensation, which ensures the delay of the echo pulses
accurately on the repetition period, with their subsequent subtraction
from the signal of the following period.

Page 146.

Since pulses impulses/momenta/pulses from the motionless
objects/subjects from one period to the next have constant amplitude,
after subtraction they completely are compensated, and on screen of
indicator the marks only of the moving/driving targets remain.

Such radars, which work with high porosity of pulses possess good
quality of selection of moving/driving targets and completely
satisfactory range resolution to target, determined by delay time of
echo pulse of that of relatively sounding signal. The angular
coordinates of target are determined by antenna directivity.

However, radars of high porosity virtually cannot achieve
precision determination of speed of motion of target due to presence
of stroboscopic effect. In such radars the speed of the motion of
target can be measured unambiguously only when it is made the
inequality

$$F_{\text{я}} \cdot \frac{F_{\text{и}}}{2} , \tag{3.30}$$

where $F_{\text{и}}$ - pulse repetition frequency of transmitter. Actually,
resulting signal (3.29) will be the single-valued function of the
argument $\Omega_{\text{я}}(n-1)T_{\text{и}}$ under the condition

$$\Omega_{\text{д}}(n-1)T_{\text{п}} < \pi, \text{ or } (n-1)F_{\text{д}} \leqslant \frac{F_{\text{п}}}{2}. \qquad (3.31)$$

During cross-period subtraction, i.e., with n=2 this inequality takes form (3.30).

Quality of operation of pulse-modulated radar with SDTs is determined by the same factors, as continuous-wave radar:

- with degree of selection of signals, reflected from moving targets, against the background of reflections from stationary objects;

   - by sensitivity on reception of such signals;

   - by accuracy of determination of parameters of motion of target.

Degree of multiple-echo compensation from motionless objects/subjects, expressed as coefficient of suppression

$$\Gamma_{\text{дб}} = -10\lg\frac{P_{\text{вх}}}{P_{\text{вых}}}, \qquad (3.32)$$

where $P_{\text{вх}}$ - power of signal from stationary target at input of system, is the main work quality factor of such radars; $P_{\text{вых}}$ - uncompensated for remainder/residue of this signal in end device. Usually the coefficient of suppression must be more than 10-20 dB.

Page 147.

Instabilities in work of separate nodes of radar and, first of all, instability of local oscillator, as which, as a rule are used reflex klystrons, can significantly limit degree of compensation for signals, reflected from motionless objects/subjects, causing parasitic amplitude, frequency and phase modulation of these signals. The

stringent requirements are imposed on the stability of the oscillations of heterodyne, since the degree of the effect of the instabilities of its frequency depends from the transit time of the sounding signal to the object and vice versa, while the instability of the frequency of transmitter is developed only for the time of the pulse duration.

In continuous-wave radar fundamental reason for limitations in degree of selection of moving/driving targets was leak of signal of transmitter from transmitting antenna into receiving, and also presence of powerful/thick reflections from adjacent motionless objects/subjects, which generate analogous effect.  This is connected with the fact that the reception of the signals, reflected from the target, is conducted continuously.

In pulse-modulated radar sounding signal and signal, reflected from target, are divided in time.  Because of this the leak of the pulse signal of transmitter into the receiving circuit, and also reflection from the closely spaced stationary targets do not limit sensitivity with respect to reception of the echo from the target signal, which arrives after the time of "echo", i.e., the time, necessary for the propagation of electromagnetic vibrations to the target and vice versa.

However, instabilities of signal of heterodyne significantly affect signal discrimination of moving/driving targets against the

background of reflections from stationary targets, arranged/located in immediate proximity of target (for example, artificial reflectors), since modulation of signals, reflected from motionless objects/subjects, is caused. Therefore the signals of stationary targets at the output of phase discriminator will be the sequence of pulses with the fluctuating amplitude. Thus, the degree selection of the moving/driving targets and the sensitivity of receiver (and consequently, and detection range and the size/dimension of the detected targets) are limited to the instabilities of the oscillations of the local oscillator.

Let us examine in more detail limitation, which superimpose instabilities of signal of heterodyne on characteristics of pulse-modulated RLS indicated.

Page 148.

Let us rewrite expression (3.28): $u_{вых} = U_{вых}(1 + m \cos \varphi_{uo})$. Here $\varphi_{uo}$ characterizes phase displacement of the signal of fixed target relative to the reference signal of coherent heterodyne at the output of phase discriminator. Is obvious the constancy of signal amplitude, reflected from fixed targets $(u_{вых})$, it is provided with the constancy of the amplitude of coherent heterodyne and with the constancy of phase displacement $\varphi_{uo}$.

With ideal work of transmitter and coherent heterodyne decisive effect exerts instability of phase (frequency) of oscillations of

local oscillator, which leads to instability $\varphi_{uo}$. Instability $\varphi_{uo}$ under the assumption that the speed of frequency drift of heterodyne is constant for time $T_n$ relative to initial frequency $(\omega_{ro})$, is expressed so [60]:

$$\Delta\varphi_{uo} = \varphi_{uo(n+1)} - \varphi_{uo(n)} = \int\limits_{(n+1)T_n}^{(n+1)T_n+t_u}\left[\omega_{ro}+\frac{d\omega_r(t)}{dt}\,t\right]dt -$$

$$-\int\limits_{nT_n}^{nT_n+t_u}\left[\omega_{ro}+\frac{d\omega_r(t)}{dt}\,t\right]dt = \frac{d\omega_r(t)}{dt}T_n\,t_u. \qquad (3.33)$$

From this expression it is evident that fluctuations $\varphi_{uo}$ are determined by instability of phase change of oscillations of heterodyne for time of "echo" $(t_u)$ from one repetition period to another. When the spurious modulation of the frequency of the local oscillator is present, the maximum values of fluctuations $\varphi_{uo}$ will occur with the periods of this modulation

$$T_u = T_n\frac{2}{2k+1}, \qquad (3.34)$$

where $T_u$ - period of spurious modulation; k=0, 1, 2... Actually, precisely, with relationship/ratio (3.34) for time $T_n$ maximum frequency drift of heterodyne will be observed.

For example, at repetition frequency $T_n = 1000$ Hz most dangerous will be fluctuations of frequency of local oscillator (with k=0) near 500 Hz, since under these conditions compensation for signals of stationary targets will be minimum. And vice versa, with the relationship/ratio

$$T_u = \frac{T_n}{k} \qquad (3.35)$$

the frequency instabilities of heterodyne virtually do not affect the quality of operation of radar.

Page 149.

Thus, for pulse radar with SDTs value of uncompensated for remainder/residue at selector output virtually is determined by frequency fluctuations of local oscillator near half repetition frequency $F_n$.

If we consider that necessary short-term relative frequency stability of local oscillator for early-warning radar during repetition period comprises $3 \cdot 10^{-9} - 10^{-9}$ (10-30 Hz at frequency of heterodyne 10 GHz) [64], then value of permissible spectral density of frequency fluctuations of local oscillator, this ensuring stability, must lie/rest within limits of 0.1-1.0 $Hz^2/Hz$ in region of Doppler frequencies of 0.1-5 kHz.

In conclusion one should note that requirements on frequency stability of klystron oscillators in coherent systems of continuous and pulse radiations/emissions in practice cannot be provided without application of any supplementary measures for increase in frequency stability of these generators. However, for the systems of continuous radiation/emission, as a whole, these requirements more rigid and with more difficulty are realized in practice than for the coherent-pulse radars.

Furthermore, it is necessary to have in mind that actual
conditions of operating klystron oscillators of stability of their
sources of instability, but also environmental factors (vibration,
acoustic effects of pulsation of supply voltages, etc.). All this,
naturally, must be considered during the creation of radar systems and
klystron oscillators. In this case maximum reduction in all external
destabilizing factors is an indispensable condition for the stable
work of the generators of shf.

Page 150.

Chapter 4.


WAYS OF REDUCTION IN THE NOISES OF KLYSTRON OSCILLATORS.

1.  Noise reduction in electronic flux of klystron.


Decrease in level of fluctuations of frequency is fundamental problem, which appears during design of low-noise generator klystrons. During correct selection of mode/conditions the works of the klystron of the fluctuation of amplitude are small and the special measures, directed toward their decrease, to accept it is not necessary, at least until frequency noises are reduced.


Other conditions being equal, level of fluctuations of frequency and amplitude of oscillations will be lower, the less intensity of noise currents in electron beam.  In connection with this, first of all, let us pause at the requirements for the construction, mode/conditions and technology of the klystrons, which emerge from the need for reduction in the noises in by electron flow.


1.1.  Low-frequency noises of electronic flux.


Low-frequency noises of electronic flux are connected not only with phenomena in cathode, but also with current interception (noises of current distribution and secondary emission).  Strictly the cathode noises include shot, the flicker noises of cathode current,

high-speed/high- velocity noises.  In those sections of the electronic

flux, where necked of current, the noises of current distribution and

the noises of the secondary emission appear additionally.  Both named

noise sources can contain flicker-components (surplus flicker noise).

Finally, the noise level of cathode current can increase due to

modulation of the depth of the minimum of potential by the ions, which

are formed in the instrument with the ionization of the molecules of

residual gas and (in the case of reflex klystron) by the electrons,

which return after operating cycle to the cathode.  The multiplicity

of noise source shows that the problem of reduction in the total noise

of electronic flux is far from simple.  It is also complicated by the

fact that some of these sources are studied insufficiently.

Page 151.

Simple enumeration of measures, by which it is possible to

decrease intensity of that or another component of noise, is hardly

useful, since difference in physical nature of noises can lead to

contradictory recommendations.  In order to avoid this, it is

necessary to isolate the most "dangerous" noise sources, utilizing

data of experiments and evaluations/estimates, similar to those led in

S 3 Chapter  1.  The criterion of the "danger" of noise source is not

only its intensity, but also degree of effect during the fluctuation

of the oscillation of generator, first of all during the fluctuation

of frequency.  It should be stipulated that not all results of this

analysis they are universal, i.e., they are applicable by klystron

oscillator of any classes and constructions/designs; however, some

general conclusions can be drawn.

1.  Most dangerous at low frequencies (lower than units of kiloherz, sometimes ten kilohertz) are flicker noises, whose intensity grows/rises with decrease of frequency.

2.  In majority of cases effect of surplus flicker noise predominates.  The flicker noise of the current of cathode, as a rule does not play the significant role.

3.  At high frequencies of fluctuations (ten, hundreds of kilohertz), where intensity of flicker noises substantially falls, surplus noises with uniform spectrum (noises of current distribution and secondary emission) present greatest danger.

4.  With reference performance of cathode (limitation of current by space charge) and sufficiently fine vacuum effect of shot and ionic noises need not be considered.

These conclusions/outputs make it possible to make important conclusion:  for decrease in level of fluctuations in klystron oscillators it is necessary to, first of all, reduce intensity of surplus noises, which appear during current interception.  Said correctly both with respect to span and with respect to reflex klystrons.  In connection with this let us examine the having the capability of reduction in the noises.

Noises of current distribution.  Energy noise spectrum, which appears in the ray/beam with the interception of electrons by positive electrode (grid) with the transparency $\beta$, is given by formula (1.22) · - ‒

$$W_{\tau} = (1 - \beta)\beta 2\,e I_{\text{к}}.$$

This formula does not consider flicker effect; it relates only to noise with uniform spectrum.

Page 151.

In spite of the fact that, as a rule $\beta$ differs little from 1, dependence $W_{\tau}(\beta)$, determined under these conditions by factor $1 - \beta$, it is sufficiently strong.  For example, with the change $\beta$ to 0.8 from 0.9 energy spectrum $W_{\tau}$ varies almost two times.  Therefore the straight/direct method of a decrease in level $W_{\tau}$ is the decrease of the losses of current on the intercepting electrode, i.e., maximum approximation/approach $\beta$ to 1.  In the low-voltage klystrons with the grids this is achieved by the improvement of the construction/design of grids (by increase in their transparency) and by the application of electron optics, which decreases the losses of electrons on the electrodes.  The coefficient of transmission of the grids, developed at the present time, is led to 0.9-0.95 and hardly it can be substantially improved.  In the improvement of electron optics is a specific reserve.

In high-voltage klystrons (in essence of span) gridless gaps are used, and in static behavior of work of loss of current they can

virtually be absent.  However, in the mode/conditions of generation
dynamic transverse degrouping increases the losses of current, and the
noises of current distribution can be revealed entirely.  Therefore
the construction/design of klystron must provide the minimum of the
losses of current precisely in the dynamic behavior.  This is achieved
by a reasonable increase of the diameter of the tube of drift in the
region of the output gap, where the flow is grouped most strongly, by
the decrease of the length of drift and by reduction in the perveance
of ray/beam.

It is possible to also utilize magnetic focusing, if this is
admissible on general conditions of applying klystron.  One should
note that rigid type magnetic focusing (with the cathode, lowered in
the magnetic field) is more preferable, since with a magnetic-shielded
cathode in the region of gun the freedom of the transverse
displacements of electrons is retained.  Since the noise of current
distribution is maximum when the probability of contact of electrons
from any point of cathode with the intercepting electrode it is
identical, then with the equal losses of current the noise level of
current distribution with the rigid magnetic focusing must be less.

Everything said above relates not only to noises of current
distribution with uniform spectrum, but also to flicker noise of
current distribution.

Let us recall that flicker noise of current distribution is

partially connected with properties of cathode (see S 3 Chapter 1),
since this noise depends on slow fluctuations of angles of emission of
electrons from surface of cathode (i.e. transverse component initial
velocity of electrons). Therefore the decrease of the grain size of
cathode and an increase in the uniformity of its emissive properties
must favorably affect also the noises of current distribution.

Page 153.

Noises of secondary emission. Since the secondary-electron noise
acts on the generatable oscillations, modulating the electronic
conductivity of gap, for reduction in the effect of this noise source
it is necessary to attempt to decrease the strength of current of the
secondary electrons, which intersect gap. Secondary electrons are
formed upon contact of primary with positive electrodes. In the final
analysis entire primary flow of electrons settles on positive
electrodes; however has a value that, as this occurs. It is necessary
to approach that so that the primary electrons would be scattered,
mainly, out of resonator gaps, and the entry/incidence of the
dislodged/chased secondary electrons into the gaps would be
hindered/hampered.

From formula (1.24) it follows that spectral density of
secondary-electron noise is proportional $(H-\bar{\sigma})\,\bar{\sigma}\bar{I_1}$, where $\bar{\sigma}$ —
secondary-emission coefficient; $H \approx 1.5\,\bar{\sigma}$, while $\bar{I_1}$ — current of primary
electrons, which determines secondary emission. Besides the decrease
of value $\bar{I_1}$, further reduction in the secondary electronic noise can

be achieved/reached by the application of coatings with the low value

of secondary-emission coefficient.  Of course, the electrical

properties of this coating on shf must be satisfactory.

Let us note that increase in transparency of grids, desirable for

reduction in noises of current distribution, usefully also for

decreasing noises of secondary emission, since virtually all

electrons, dislodged/chased from grids, fall into gap.

In gridless span klystrons secondary-electron currents can be

large even in complete absence of current interception in region of

drift and in gaps.  This is connected with the secondary emission from

the collector/receptacle.  Therefore design of collector/receptacle

must be such that the probability of the output of secondary electrons

into working the space of klystron would be minimum.  In such cases,

when this is not provided, it is possible to recommend an increase in

the potential of collector/receptacle on 30-50 $V$ relative to the unit

of resonators.  The potential threshold of this value is sufficient

for preventing the yield of bulk of secondary electrons from the zone

of collector/receptacle.

One should emphasize that decrease of number of secondary

electrons in operating region of klystron is necessary not only for

reduction in intensity strictly of secondary-electron noises, but also

for weakening of noise effect of primary electrons, since fluctuations

of secondary- electron current are determined not only by fluctuations
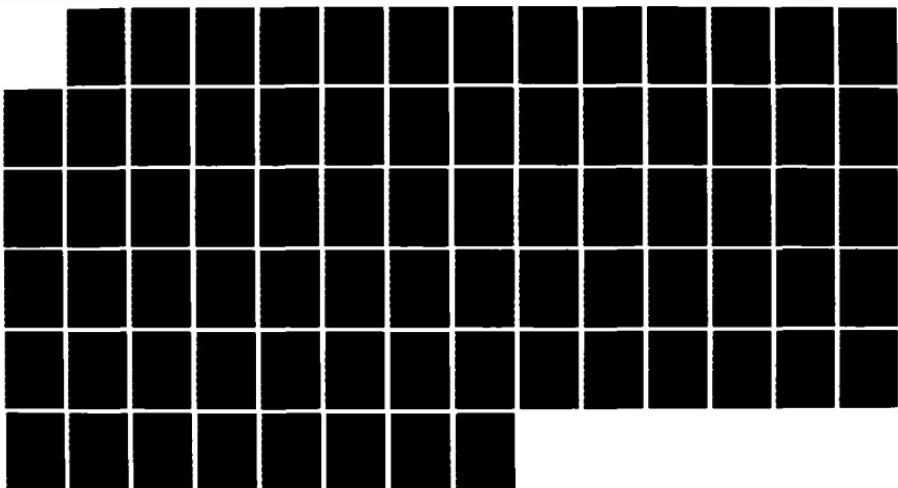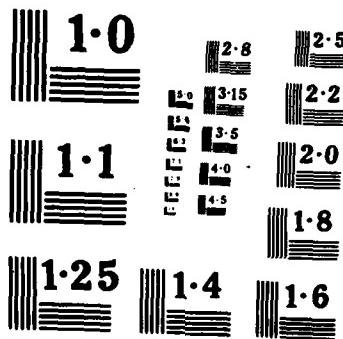
of secondary-emission coefficient, but also by fluctuations of primary current [see formula (1.23)].

Page 154.

Flicker effect in current of cathode. Above it was said, that the low-frequency noises of emission play secondary role in comparison with the surplus noises. However, during the suppression of the action of surplus noise source the role of the flicker noise of cathode current can increase. Therefore a question the methods of reduction in the flicker noise of emission deserves attention.

General measures for decrease in level of flicker noise of oxide cathodes, recommended on the basis of practical experience, are reduced to reduction in density of current removed from cathode, increase in uniformity of emission, lower resistor/resistance of high-impedance layer of cathode. Since even the local poisoning of cathode is capable of leading to a noticeable increase in the noises, more stable noise characteristics have the saturated cathodes, less sensitive to the poisoning.

In the case of reflex klystrons level of flicker noise of cathode current is increased due to action of effects, which do not occur in span klystrons.

In operational conditions part of electrons after flight/span in damping field again returns to cathode and is changed space charge

near the cathode, and consequently, and depth of minimum of potential

near the cathode.  Since in the current, comprised by these electrons,

is contained the flicker noise of current distribution, which arose

with the interception of the remaining part of the current by positive

electrodes, the depth of the minimum of potential is modulated by this

noise.  This, in turn, it leads to supplementary modulation of cathode

current.  As a result the total level of the flicker noise of cathode

current is raised, sometimes considerably (by an order) [1].

FOOTNOTE [1].  Its own flicker noise of the current of the cathode of

reflex klystron can be measured only with the positive potential of

the reflector, when the return of electrons to the cathode is

impossible.  ENDFOOTNOTE.

Confirmation about secondary role of flicker noise of cathode

current, made earlier, remains valid even in such cases, when

supplementary component of flicker noise is great, since its level is

reflection of level of flicker noise of current distribution, which

directly modulates oscillation.

Page 155.

1.2.  Shf/SVCh noises of electronic flux.

So as low-frequency noises, shf noises of operating region of

electronic flux of low-free klystrons are caused by not so much

initial noises of emission, as by surplus noises, which appear as a

result of nonlaminar nature of flow, convergence of electron paths and current interception (see S 2 Chapter 1). It would seem that the contemporary electron-optical systems make it possible to weaken/attenuate the effect of all these factors. For example, constructions/designs of the multianode electron guns, which ensure the very low level shf, are known; however, they are developed for input LBV, where are utilized light currents comparatively high voltages with the rigid magnetic focusing. To transfer these methods of engineering the guns to low-voltage reflex klystrons is virtually impossible, and it is far from simple this to make for generator span of klystrons.

First of all this is connected with the fact that magnetic focusing in reflex klystrons is unsuitable, and noises of current distribution, which associate current interception with freedom of lateral motions of electrons, are virtually nonremovable. Furthermore, the high perveance of ray/beam requires and the special electron-optical solutions. Finally in reflex klystrons the minimum of potential near the cathode is agitated by the space charge of the part of the electrons reflected, which penetrate to the cathode. The goal-directed studies of a decrease in the level of shf noises in the electronic fluxes of reflex klystrons was not carried out, and therefore at present it is possible to give only the general recommendations: were preferable the weakly convergent electronic fluxes, close ones possible to the laminar; the loss of current on the grids must be minimum.

Experiments show that level of shf noise current in resonator gap of usual reflex klystrons of short-wave part of centimeter band is of the order of complete shot noise.  If we assume that all excess noises, except the noises of current interception, supressed by the successful construction/design of gun, and even then the level of shf noises of ray/beam will be lowered by no more than an order (as noted above, the real ways of an increase in the transparency of grids to the value, greater 0.9-0.95, evidently).

In generators on span klystrons with high-voltage power supply and gridless gaps, apparently, it is possible to achieve somewhat larger reduction in shf noises of current interception.  It is natural that technical equipment for this the same as examined above in connection with the problem of reduction in low-frequency component of the noise of current interception.

Decrease in level of surplus shf noises, connected with nonlaminar nature and convergence of electronic flux, is provided by final adjustment of electron-optical system of klystron, during design of which one should approach variant, which is characterized by smallest compression of ray/beam into guns and smallest current density of ray/beam in operating region [102].

Page 156.   The possibility of designing of low-power generators on the span klystron with the use of the multielectrode low-noise guns, developed for input LBV, virtually was not investigated.

2. Decrease in the level of the fluctuations of the generatable oscillation (requirements for the mode of operation and construction/design of klystron).

2.1. Uniform components of spectra of fluctuations.

On the basis of formulas (1.69), let us record expressions for spectral densities of fluctuations, after taking into consideration only most essential sources of noises (in accordance with evaluations/estimates, made in S 3 Chapter 1):

$$(W_a)_{\text{полн}} \approx (W_{aa})_i + (W_{aa})_v.$$

where

$$(W_{aa})_i = \Phi_{ai} \frac{W_i(\overline{f})}{I_0^2} ;$$

$$(W_{aa})_v = \overline{\theta}^2 \left( \frac{\omega_p}{\overline{\omega}} \right)^2 \Phi_{av} \frac{W_i(\overline{f})}{I_0^2} ,$$

and

$$(W_f)_{\text{полн}} \approx (W_{f\varphi})_i + (W_{f\varphi})_v + (W_{f\mu})_\tau + (W_{f\mu})_o ,$$

where

$$(W_{f\varphi})_i = \left( \frac{\overline{f}}{2Q_{\text{н}}} \right)^2 \Phi_{fi} \frac{W_i(\overline{f})}{I_0^2} ;$$

$$(W_{f\varphi})_v = \left( \frac{\overline{f}}{2Q_{\text{н}}} \right)^2 \overline{\theta}^2 \left( \frac{\omega_p}{\overline{\omega}} \right)^2 \Phi_{fv} \frac{W_i(\overline{f})}{I_0^2} ;$$

$$(W_{f\mu})_\tau = \left( \frac{\overline{f}}{2Q_{\text{н}}} \right)^2 \left( \frac{\overline{b}_c}{g} - 2\overline{v} F_i \right)^2 \frac{(1 - \beta) 2e}{\beta \overline{I}_{\text{к}}} ;$$

$$(W_{f\mu})_o = \left( \frac{\overline{f}}{2Q_{\text{н}}} \right)^2 \left( \frac{\overline{b}_{c2}'}{g} \right)^2 \frac{2e (H - \overline{\imath}) (\overline{I}_2' + \overline{I}_1')}{(\overline{I}_2')^2} .$$

Using these expressions, let us examine requirements for

operating modes, parameters and construction/design of klystrons.

Requirements for mode/conditions of grouping.  Dependence $(W_a)_{p\text{a\text{a}\text{a}}}$ on bunching parameter X is determined by coefficients $\Phi_{a l}$ and $\Phi_{a v}$. From formulas (1.64) and graphs/curves in Fig.  1.10a it follows that $\Phi_{a l}$ and $\Phi_{a v}$ decrease with increase/growth X at first sharply, and when X≥1.8 - slowly.

Page 157.

With the given ones accelerating voltage and the current of ray/beam value X it is possible to control, changing connection/communication with the load and number of the zone of oscillations.  Since component $(W_a)_{p\text{a\text{a}\text{a}}}$, connected with the fluctuations of the speed, i.e., $(W_{aa})_v$, is proportional to the square of the transit angle of electrons in the decelerating field $\bar{\theta}^2$, for achievement of minimum level $(W_a)_{p\text{a\text{a}\text{a}}}$ it is necessary to utilize the lowest of the possible zones of generation, providing in it sufficiently high value with the X selection of connection/communication with the load.  If the discussion deals with the construction of klystron with minimum level $(W_a)_{\text{a\text{a}\text{a}\text{a}}}$ then during the selection of the parameters on the energy criteria should be it relied on the smallest number of the zone of oscillations.

Uniform component of spectrum of fluctuations of frequency $(W_f)_{p\text{a\text{a}\text{a}}}$ is connected with bunching parameter only to the extent of dependence of that part, which is caused by shf noise of ray/beam, i.e., $(W_{fn})_l + (W_{fn})_v$.  The dependence of these components on X is

determined by coefficients $\Phi_{fi}$ and $\Phi_{fv}$, which are minimum with X=1.8-2 [see formulas (1.64) and graphs/curves in Fig. 1.10b]. So, as $(W_{av})_v$, $(W_{fv})_v$ is proportional $\overline{\theta}^2$. This means that the condition of obtaining the minimum level of component $(W_f)_{pавн}$ of that caused by shf noises of the current of ray/beam, virtually the same as in the case of the fluctuations of amplitude examined.

Components $(W_f)_{pавн}$ caused by low-frequency noises of ray/beam $(W_{fн})_т$ and $(W_{fн})_ф$ on bunching parameter do not depend.

Requirements for parameters and construction/design of klystron. With the formulation of these requirements we will furthermore consider that accelerating voltage and current of ray/beam are assigned on the basis of the conditions of obtaining the fundamental parameters of klystron.

For decrease in level $(W_a)_{pавн}$ should be improved current flow, since basic part $(W_a)_{pавн}$ namely $(W_{av})_i$ decreases in this case due to decrease of coefficient $\Phi_{ai}$ [formula (1.64), Fig. 1.10a]. The discussion deals here not with a decrease in the level of shf noise of current distribution, but with the supplementary gain due to an increase in the operating current in the gap about this current of cathode, i.e., due to the increase efficiency. klystron. Similarly during an improvement in the current flow decreases the component of the spectral density of the fluctuations of frequency $(W_{fн})_i$ because of decrease of coefficient $\Phi_{fi}$ [formula (1.64), Fig. 1.10b].

The component $(W_a)_{\text{рави}}$ and $(W_f)_{\text{рави}}$, speeds $[(W_{as})_v$ and $(W_{fs})_v]$, caused by fluctuations are respectively proportional to square of plasma frequency $\omega_p^2$ and therefore decrease of current density of ray/beam contributes to their decrease.

Page 158.

However, this measure hardly is necessary, if for the work is selected the small number of the zone of generation, since at the usually utilized current density in this case the determining role play components $(W_{as})_i$ and $(W_{fs})_i$.

Since components $(W_f)_{\text{рави}}$, caused by shf noises of ray/beam [i.e. $(W_{fs})_i$ and $(W_{fs})_v]$, are proportional $\left(\dfrac{\overline{f}}{2Q_{\text{н}}}\right)^2$, increase in quality of loaded resonator $Q_{\text{н}}$ reduces their level to identical degree. Unfortunately, value $Q_{\text{н}}$ in the low-voltage klystrons with the grids cannot be made more than several hundred.

The of increasing oscillatory system equivalent to quality by using connected resonators will be examined into § 4.

In spite of the fact that components $(W_f)_{\text{рави}}$, caused by low-frequency noises of ray/beam, are also proportional $\left(\dfrac{f}{2Q_{\text{н}}}\right)^2$, their dependence on $Q_{\text{н}}$ has another character, since their values depend additionally on complete conductance of resonator. Let us examine these components in detail.

1.  Spectral density of fluctuations of frequency, caused by noises of secondary emission $(W_{f_H})_o$.

Taking into account that $\bar{g} = \dfrac{1}{\rho Q_H}$, where $\rho = 1/2\pi f \bar{C}$ - characteristic impedance of resonator, and also taking into account, that on (1.43)

$$\overline{b_{e2}'} = \frac{1}{\theta_g^2}\frac{\overline{\theta_{K2}}}{V_0}\overline{I_2'},$$

we will obtain

$$(W_{f_H})_o \approx \left(\frac{\bar{f}}{2Q_H}\right)^2 \left(\frac{\overline{b_{e2}'}}{\bar{g}}\right)\frac{2e\,(H-\bar{\partial})\,(\overline{I_2'}+\overline{I_2'})}{(\overline{I_2'})^2} =$$

$$\left(\frac{1}{4\pi C}\right)^2 \left(\frac{\overline{\theta_{g2}}}{\theta_g^2\,V_0}\right)^2 2e\,(H-\bar{\partial})\,(\overline{I_2'}+\overline{I_2'}).$$

Since $\overline{\theta_{g2}} \approx \dfrac{\omega d}{\overline{v_s}}$, $\theta_g = \dfrac{\omega d}{v_0}$, while $V_0 = \dfrac{m v_0^2}{2e}$, where $\bar{v}_s$ - average speed of slow (secondary) electrons, d - distance between grids of gap, finally we will obtain

$$(W_{f_H})_o = \left(\frac{e\rho}{m\overline{v}_2\,2\pi d}\right)^2 2e\,(H-\bar{\partial})\,(\overline{I_2'}+\overline{I_2'}).$$

Page 159.

Hence follows that level $(W_{f_H})_o$ does not depend on the quality of resonator and is determined by ratio $(\rho/d)^2$.

If equivalent capacity/capacitance C was determined only by concentrated gap capacitance $C_\tau$, then $\rho \sim 1/d$, and this relation would not depend on gap length.  However, $C = C_\tau + C_{\text{рясирея}}$, and therefore with increase in d level $(W_{f_H})_o$ must be reduced.  This method of decrease $(W_{f_H})$, is the more effective, the greater the relation $C_{\text{рясирея}}/C_\tau$.

Virtually noticeable gain due to an increase in resonator gap can be obtained in the high-voltage klystrons with the gridless gaps.

2. Component $(W_{f\text{ н}})_{\text{разн}}$, caused by noises of current distribution

$$(W_{f\text{н}})_\text{т} = \left(\frac{\overline{f}}{2Q_\text{н}}\right)^2\left(\frac{\overline{b}_e}{\overline{g}} - 2\overline{\theta}F_J\right)^2\frac{2e(1-\beta)}{\beta\overline{I}_\text{к}} =$$

$$= \left(\frac{\overline{b}_e}{\overline{g}}\frac{\overline{f}}{2Q_\text{н}} - 2\overline{\theta}F_J\frac{\overline{f}}{2Q_\text{н}}\right)^2\frac{2e(1-\beta)}{\beta\overline{I}_\text{к}}.$$

In connection with the fact that $\overline{b}_e = \overline{b}_{e1} + \overline{b}_{e2}$ and $|\overline{b}_{e2}| \gg |\overline{b}_{e1}|$, $\overline{b}_e \approx \overline{b}_{e2}$. If we consider that $\overline{b}_{e2} < 0$ and to replace $\overline{f}/gQ_\text{н} = 1/2\pi C$, we will obtain

$$(W_{f\text{н}})_\text{т} \approx \left(\frac{|\overline{b}_{e2}|}{4\pi C} + \frac{\overline{f}\overline{\theta}F_J}{Q_\text{н}}\right)^2\frac{2e(1-\beta)}{\beta\overline{I}_\text{к}}.$$

It is not difficult to show that the first member of bracketed expression decreases with an increase of resonator gap as in the case of the noises of the secondary emission:

$$\frac{|\overline{b}_{e2}|}{4\pi C} = \frac{\overline{\theta}_{e2}\overline{I}_2'}{4\pi C\theta_g^2 V_0} = \frac{\frac{\omega d}{\overline{v}_s}\overline{I}_2'}{4\pi C\left(\frac{\omega d}{v_0}\right)^2 V_0} = \frac{\frac{e}{m}\overline{I}_2'}{2\pi\overline{v}_s}\frac{\rho}{d}.$$

The second term in the brackets of expression for $(W_{f\text{н}})_\text{т}$ will decrease with the decrease $\overline{\theta}$ and $F_J$ and with increase $Q_\text{н}$. As a rule the second term noticeably exceeds the first, and therefore the fundamental way of decrease $(W_{f\text{н}})_\text{т}$ - increase $Q_\text{н}$, work with the small numbers of the zones of generation and with as small as possible $F_J$. Let us note that both members have identical signs and cannot average out each other.

Page 160.


## 2.2. Flicker-components of the spectra of fluctuations.


For analysis we will use expressions (1.71):

$$(W_{\text{ан}})_{\phi} = \left[ \frac{J_1(\overline{X})}{\overline{X} J_2(\overline{X})} \right]^2 \left[ \frac{W_{\kappa\phi}(F)}{(\overline{I_{\kappa}})^2} + \frac{W_{\tau\phi}(F)}{(\beta \overline{I_{\kappa}})^2} + \left( \frac{\overline{g}'_{e2}}{\overline{g}} \right)^2 \times \right.$$

$$\left. \times \frac{W'_{\alpha\phi}(F) + W'_{\alpha\phi}(F)}{(\overline{I'_2})^2} \right],$$

$$(W_{f\text{н}})_{\phi} = \left( \frac{\overline{f}}{2Q_{\text{н}}} \right)^2 \left\{ \left( \frac{\overline{b}_e}{\overline{g}} - 2\overline{v} F_J \right)^2 \left[ \frac{W_{\kappa\phi}(F)}{(\overline{I_{\kappa}})^2} + \right. \right.$$

$$\left. + \frac{W_{\tau\phi}(F)}{(\beta \overline{I_{\kappa}})^2} \right] + \left( \frac{\overline{b}'_{e2}}{\overline{g}} \right)^2 \frac{W'_{\alpha\phi}(F) + W'_{\alpha\phi}(F)}{(\overline{I'_2})^2} \right\}.$$


Fluctuations of amplitude $(W_{\text{ан}})_{\phi}$ depend on mode/conditions of grouping, since they are determined by coefficient $\left[ \frac{J_1(\overline{X})}{\overline{X} J_2(\overline{X})} \right]$. This coefficient decreases with increase $\overline{X}$ and in region $\overline{X} \geq 1.8-2.0$ is changed weakly. Thus, minimum level $(W_{\text{ан}})_{\phi}$ is provided under the same conditions as in the case of shf noises. Let us note that in the formula for $(W_{\text{ан}})_{\phi}$ the latter/last term is small due to the low value of the ratio $(\overline{g}'_{e2} \overline{g})^2$ [1].


FOOTNOTE [1]. See the evaluation/estimate, led in § 3 Chapter 1. ENDFOOTNOTE.


From formula for fluctuations of frequency $(W_{f\text{н}})_{\phi}$ it follows that all reasonings relative to ways of reduction in components $(W_{f\text{н}})_{\text{рави}}$,

caused by low-frequency noises with uniform spectrum, are valid also for frequency flicker noise, although specific contribution of different noise sources can be different.

2.3.  General considerations under the selection of construction/design and the conditions of the work of low- noise klystron of generators.

As it follows from that presented, there is series/row of general requirements for the construction and mode/conditions of work of klystron oscillator, whose fulfillment is equally useful for reduction in fluctuations, caused by action of different noise sources.

Page 161.

On the base of these requirements it is possible to formulate general recommendations, which facilitate reduction in the noises.

1.  Bunching parameter must be in limits of 1.8-2.

2.  Klystron must work with minimum number of zone of generation.

3.  Guarantee of maximum current flow is necessary.

4.  Are desirable increase in quality $Q_{\shortparallel}$ (reflex klystron) or equivalent to quality of the resonator systems (generator on span klystron).

5.  Work at low current densities of ray/beam is preferable, but current density must be reduced due to increase in sectional area of ray/beam, but not due to decrease of current strength.  However, one should consider that an increase in the sectional area of ray/beam leads to the increase of equivalent capacitance and, thus, to an increase in the ohmic losses.  Therefore an excessive increase in area of beam can, in the final analysis, cause the need for transition/junction to the work into the zone with the large number, and this, as it is said above, it is undesirable.

6.  During selection of construction/design, materials and technology it is necessary to approach guarantee of minimum value of secondary-emission currents in klystron.  In particular, it is necessary to ensure the finish of the surfaces, bombarded with electrons.  When the frequency noise, caused by the secondary emission, is great, it is expedient for its decrease to increase high-frequency resonator gap even to the detriment of the output parameters [1].

FOOTNOTE [1].  This procedure was successfully used in work [93], where due to an increase in the gridless gap was obtained gain on the fluctuations of frequency approximately on 10 dB.  Let us note that into [93] it is not given the satisfactory explanation of the obtained result, but the given there experimental material will agree well with view presented here on the character of the effect of

secondary-electron noise.  For example, into [93] is noted the absence of the dependence of the level of frequency noise on the accelerating potential, maintaining the level of the fluctuations of amplitude with an increase in the gap.  ENDFOOTNOTE.

7.  Preferable are electron-optical systems with small convergence and maximum laminarity of ray/beam.

8.  Guarantee of uniformity of emission over surface of cathode (absence of local disturbances/breakdowns of emission) is necessary. Cathodes with the flat surface (for example, the pressed saturated cathodes) are preferable.

9.  Reduction in current density, removed from cathode, and decrease of resistor/resistance of layer, is desirable.

Recommendatiohs presented are valid both for reflecting and for span klystrons.

Page 162.

Let us note that for the span klystrons with the gridless gaps additionally one should decrease the perveance due to increase $V_o$ [31].  This measure leads for the decrease of the effect of space charge in the region of drift and for reduction in the electronic conductivity.

3.  Suppression of regular component in the spectra of fluctuations generatable oscillations.

3.1.  Decrease of probability of appearance of vibration regular component in spectrum of fluctuations of frequency oscillations.

In connection with this the fact that to completely remove mechanical oscillations of parts of klystron under external influences (especially at resonance frequencies) is impossible, one cannot radically solve problem of guaranteeing complete suppression of vibration regular components.  But to decrease the intensity of such components to the in practice acceptable level under the actual conditions for operation is possible.  In this case satisfactory results can be obtained only by combined efforts/forces of the developers of equipment and the developers of klystron oscillators.

First, maximally possible decrease of accelerations of external vibration effect is necessary.  The lower the noise level of klystron oscillator, the lower must be the values of external vibration effects to avoid appearance in the noise spectra of noticeable vibration regular components.  Reduction in the values of vibrational accelerations to 1-3 g by using the usual methods of damping equipment makes it possible to use klystron oscillators with the improved noise characteristics on the movable objects.  However, the need for further sharp decrease in the values of vibration effects for using the klystrons with the especially low noise level is complicated technical problem and limits the field of application of similar klystrons.

Their protection from sonic or ultrasonic effects is very important operating condition of low-noise klystrons, since with coincidence of frequency of effect with resonance frequency of mechanical oscillations of grids, walls of resonator, unadjusted elements/cells or other parts, on position of which strongly depend output parameters of klystron, in spectrum of fluctuations appear intense regular components. The frequencies of these components usually lie/rest at operating regions of Doppler range (§ 4 Chapter 1). Let us recall that by the reason for the excitation of the mechanical oscillations of parts at the resonance frequencies can be the poor attachment of the elements/cells of the mounting of equipment or klystron itself. In connection with this during design of the low-noise klystrons should be paid special attention to the reliability of the interconnection of parts and assemblies for the exception/elimination of the possibility of their friction or rapping against each other. Thus, for example, the pistoning of insulators and their attachment with the method of reduction is recommended to replace by soldering, in the constructions/designs must not be, if possible, such fine-adjustment elements/cells, which would not be soldered or poured by hard resins.

One complex problem from point of view of possibility of mutual displacement is node cathode - heater. For the attachment of heater in the cathode is completely necessary the use of one or the other technological processes, capable of ensuring reliable fixation of

heater with high temperatures and with changes in the temperature, which correspond to different operating conditions. However, the methods of the filling of heater in the cathode by Alundum or with other masses, sintering the spiral of heater with the ceramic rod lead to an increase in the inertness of cathode, raise respectively the readiness time of klystron and therefore they frequently prove to be unacceptable. In these cases it is possible to utilize the mechanical squeezing of heater or other methods of mechanical attachment [70].

Construction/design of low-noise klystron must be maximally rigid; therefore for mechanical retuning of frequency of klystron preferably use of system of connected resonators, but not change in air-gap clearance of resonator or introduction to cavity of evacuated resonator of tuning element. The advantage of the system of the connected resonators is determined by the absence of flexible walls, membranes/diaphragms or bellows, which are necessary for the retuning of the single evacuated resonator, and also by the substantially smaller slope/transconductance of mechanical retuning.

Grids, which form resonator gap, must be either monolithic (honeycomb type grid, grids, made electrical errosion method in continuous metal), or loop tungsten [101]. is not recommended the using of for resonator gaps of the low-noise klystrons wire woven grids and especially grids with nodes not soldered through in the places, where the turns of wire are intersected. It follows to avoid the formation of long brackets during design of electron guns,

assemblies of reflector and collector/receptacle.  Especially this concerns high-voltage klystrons.

Page 164.

Most expedient is a cermet overall design of low-noise klystrons. It makes it possible to achieve the maximum rigidity of construction/design and to most fully utilize contemporary technology, which provides reliability and life of klystron, the stability of characteristics.

3.2.  Decrease of the probability of the appearance of static regular component in the spectra fluctuations.

By most important condition of guaranteeing reliable work of low-noise klystron and, in particular, condition of decreasing probability of appearance of static regular components is obtaining required vacuum in working klystron and preservation of both the value of pressure and spectral composition of residual gases in process of operation.  For reflex klystron the pressure of residual gases must not exceed $10^{-7}$ mm Hg, while for span $10^{-8}$ and even $10^{-9}$ mm Hg [1].

FOOTNOTE [1].  Fulfilling these requirements provides the low value of the fluctuation noise of ionic origin.  ENDFOOTNOTE.

In this connection during production of low-noise klystrons it is necessary to use cleanest materials (for example metals, melted in

vacuum), contemporary methods of cleaning parts and assemblies and their degassing. Evacuation with the dual vacuum (vacuum not only inside, but also outside the evacuated klystron), is preferable, since in this case is feasible warm-up at maximum temperatures (to 700-800°C). Warm-up at such temperatures not only contributes to the best degassing of parts, which raises the stability of vacuum in the process of operation, but also decreases deposition of the products of activation of cathode by the internal walls of the nodes of klystron and decreases the probability of oxide coating. All this must favorably affect both total noise level and the suppression of secondary electrons static regular component because of the decrease of a quantity.

Use of effective getters is desirable, but are preferable unsprayed getters.

All recommendations presented above carry technological character [2]; however, without taking into account specific requirements for the construction most ideal technology can prove to be barely effective in fight with static regular components.

FOOTNOTE [2]. In more detail with questions of contemporary technology of electronic devices the reader can be introduced, for example, in [65, 66]. ENDFOOTNOTE.

Page 165.

First conditon during design construction of klystrons is such selection of sizes/dimensions of electron-optical system, during which is impossible formation of virtual cathode.  If according to one or the other reasons the lengths of the span religious rites of grid klystrons cannot be made deliberately less than critical, then for the difficulty of the formation of virtual cathode it is possible to recommend the use of the increased opening/aperture in the center of accelerating grid (usually its diameter of approximately 1.5 mm), which changes axial potential distribution [67].  For achievement of the same target it is possible to utilize a separation of the tube of drift into several parts - channels - with the aid of the thin metallic partitions/baffles or other methods [68].

It is important however, to recall that absence of virtual cathode is necessary, but insufficient condition for suppression of relaxation or plasma oscillations in klystron, which call appearance of static regular components (S 4 Chapter  1).

Therefore one should approach complete elimination in entire electron-optical system of klystron of ion traps, although in many instances solution of this problem is conjugated/combined with very great difficulties, and sometimes it is in principle impossible.  In connection with this for the low-noise klystrons are preferable the electron guns, which work without accelerating grid or with the voltage/stress between accelerating grid and cathode, considerably lower than voltage/stress cathode - resonator.

For eliminating potential wells in region of tubes of klystrons it is possible to use smooth or abrupt change of diameters of tubes, which facilitates compensation of potentials along axis of electronic flux [69].

Should be mentioned about method of suppression of static regular components with modulation of electronic flux of klystron with frequency to 2-3 orders of of higher than frequencies of static regular components.  It is experimentally established that even with the small depth of modulation on the current to virtually completely it is possible suppress static regular components.  Unfortunately, this method, on one hand, complicates the construction/design of klystron and its feed, and on the other hand, it is not applied in many instances on operating conditions.

4.  Radio engineering methods of noise reduction of klystron generators.

Level of frequency noises of klystron oscillators can be substantially improved by application of special radio engineering methods, which facilitate increase in stability of generatable frequency.

Page 166.

In the principle, any method of frequency fixing of the generators of

shf can successfully be used for a decrease in the level of the frequency noises (with exception, certainly, the methods of increasing the stability of the generatable frequency due to weakening of the effect of the external destabilizing factors, for example, by thermostating, damping, decreasing the pulsations of the supplies of power, etc.).

Monograph [71] is dedicated to methods of frequency fixing of generators of shf. Will be examined below only the two widespread methods of stabilization of klystron oscillators:  stabilization via the automatic frequency control (APCh) and parametric stabilization with the use of an external high-Q resonator.  The first method is used almost exclusively for the stabilization of reflex klystrons, what is connected with convenience in the frequency control with a change in the voltage on the current-free electrode - the reflector, the second - for the stabilization both of reflecting and span klystron oscillators.

4.1.  The automatic frequency control.

It is most full problems, connected with theory, by design and by application of APCh, they are presented in labor/works [71, 72].  The essence of the method of the automatic frequency control consists in the comparison of the frequency (phase) of the stabilized generator with the frequency (phase) of supporting/reference standard, generation of the error signal, connected with a difference in these

frequencies or phases, and effect by this signal on the generator for the purpose of the maximum decrease of the error signal.

Fundamental system block diagram of APCh is given in fig.  4.1. Part of power of stabilized generator is branched/shunted to device/equipment, called discriminator, in which is conducted comparison of frequency of generator and standard.
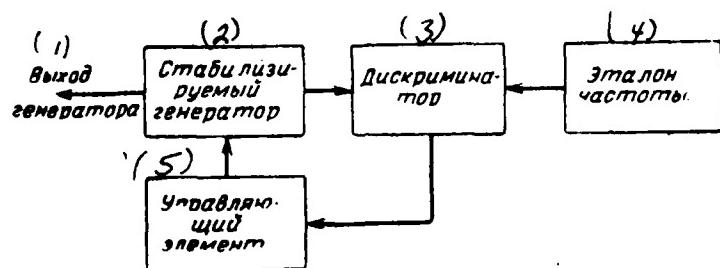
Fig. 4.1. System block diagram APCh.

Key: (1). Output of generator. (2). Stabilized generator. (3). Discriminator. (4). Frequency standard. (5). Control element.

Page 167.

If the compared frequencies are different, then at the output of discriminator will appear the error signal, value and sign of which depend on value and sign of a change in the oscillator frequency. The error signal, acting through the control element on klystron, changes oscillation frequency to the side, reverse/inverse initial detuning.

Since change in frequency of generator is unambiguously connected with change in phase of oscillations, the is possible comparison of oscillations of stabilized and standard generators both in frequency and on phase. Theoretically comparisons and device/equipment of the discriminator (sensor of disagreement/mismatch) of system of APCh are divided into the frequency (ChAP) and the phase (FAP). In the system of frequency self-alignment the error signal is connected with a difference in the frequencies of the adjustable/tuneable generator and standard. The resonance frequency of cavity resonator is usually standard frequency. In the system of phase self-alignment the error

signal is determined by a phase difference of the oscillations of the adjustable/tuneable generator and standard.

This difference in these systems with respect to working principle of sensors of disagreement/mismatch causes different character of dependence of divergence of frequency of stabilized generator relative to standard from value of destabilizing effect. According to the character of this dependence the systems of APCh are divided into the static, in which residual/remanent error depends on the value of the initial detuning, and astatic, in which residual/remanent error vanishes independent of initial detuning.

Systems of APCh are characterized by following fundamental parameters:

- by coefficient of self-alignment or by stabilization factor, which is expressed by ratio of values of initial detuning of generator to residual/remanent

$$K_{ci} = \frac{\Delta f_{\text{н}}}{\Delta f_0} . \qquad (4.1)$$

In such a case, when detuning occurs as a result of regular or chaotic modulation of fundamental oscillator frequency, stabilization factor, generally speaking, is the function of the frequency of this spurious modulation. In other words, stabilization factor is various for slow and rapid changes in the oscillator frequency;

- range of the retention, which determines the maximum permissible interval of the divergences of oscillator frequency within which is retained effective work of in the established/installed

mode/conditions;

- by trapping range, which determines the maximum permissible initial divergences of oscillator frequency, with which is feasible the capture of this frequency and transition/junction to the mode/conditions of retention.

Page 168.

Frequency self- alignment (ChAP). The widespread diagram of frequency self-alignment with the waveguide discriminator and the error signal at the intermediate frequency is given in Fig. 4.2.  The fundamental network elements are:  dual waveguide tee with those placed in its arms by resonator (frequency standard), phase inverter and two semiconductor detectors; generator of intermediate frequency; buffer amplifiers; phase-sensitive detector and control system.

Let us examine the working principle of diagram.  High-frequency oscillation from klystron oscillator comes into arm H of twin T-piece.  Because of the symmetry of device/equipment the wave, which enters this arm, excites in the lateral arms of the waves, co-phasal and equal in the amplitude.  With the identity of lateral arms the wave in arm E is not excited.

Connection/communication of cavity resonator with waveguide in one of lateral arm is selected such that at frequency $f=f_0$ resistor/resistance of resonator would be equal to wave impedance of waveguide, and it presented, thereby, matched load.  Detector $\pi_1$  in

other lateral arm analogously must be agreed on at the resonance
frequency.  To the detector  $Д_1$  the signal of intermediate frequency,
which, modulating internal resistor/resistance of detector, disrupts
the coordination of arms, is supplied.  as a result the signal echo
from the detector  $Д_1$ , due to the nonlinearity of the characteristic
of detector consisting of the lateral modulation frequencies  $f_0 \pm f_{пр}$.
falls into arm E.  With a change in the frequency of klystron, $f_0$
relatively occurs the detuning also of the arm, with which is
connected the resonator.  In this case the signal echo from the
resonator, amplitude and phase of which are determined by the value of
detuning $f-f_0=\Delta f$, also falls into arm E.

As a result on detector  $Д_2$  occurs mixing of signals with
frequencies  $f, f+f_{пр}$ and $f-f_{пр}$ and is developed a voltage intermediate
frequency, amplitude and phase of which depend on value of detuning of
generator relative to standard frequency of resonator.  The intensive
signal of intermediate frequency from the detector  $Д_2$  is supplied to
the phase discriminator where simultaneously it is supplied signal
from the generator of intermediate frequency.
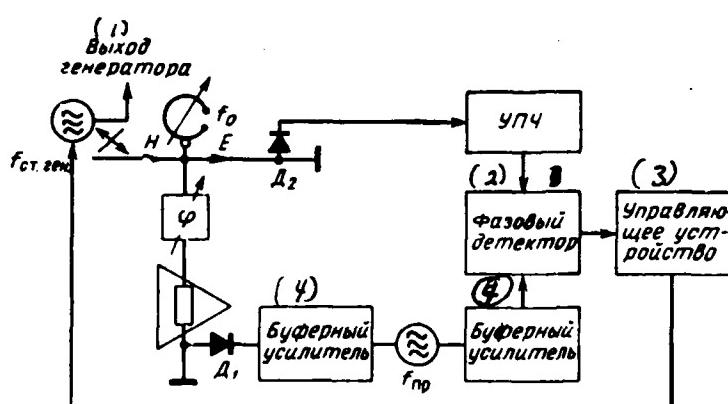
Fig. 4.2.   Diagram of frequency self-alignment (ChAP).

Key:  (1).  output of generator.   (2).  Phase discriminator.   (3).

Control system.   (4).   Buffer amplifier.

Page 169.

Phase-sensitive detector develops output voltage/stress,
proportional to phase difference of two input voltage.  Since one
signal (from the generator of intermediate frequency) has the specific
phase, and the phase of another signal depends on value and sign of
the detuning of oscillator frequency, relative to resonance, then
value and sign of output voltage/stress from the phase discriminator
also depend on value and sign of the detuning of frequency.  This
voltage/stress, called the error signal, through the control system is
supplied to the klystron repeller, reducing the value of detuning to
the minimum.

Any control system is in stable state with control pressure
remaining the same.  For the system this ChAP means that in the

steady-state mode/conditions must be supported constant output
potential of phase discriminator.  Since frequency discriminator is
the sensor of disagreement/mismatch in this system, the constancy of
voltage/stress from the phase discriminator is possible only when a
certain residual/remanent difference in the frequencies of the
generator and cavity meter is present.

Thus, in diagram ChAP is always residual/remanent detuning of
frequencies, which depends on value of stabilization factor.  In this
sense this diagram is static.  under the influence on the klystron of
disturbance/perturbation with the frequency, close to zero ("slow"
drifts), in the diagram of ChAP the residual/remanent static error,
which decreases with an increase in the stabilization factor, will
occur.

Characteristics of system of ChAP with respect to "rapid"
frequency drift of klystron are determined by its dynamic properties.
In view of the inertness of the separate elements of network
(discriminator, IF amplifier, phase-sensitive detector) the transfer
function of system is frequency-dependent, and phase change in the
system increases with an increase in the frequency of spurious
modulation.  Stabilization factor in this case from an increase in the
frequency falls, approaching one at the modulation frequency F,
striving toward certain critical value $F_{\text{пр}}$ [1].

FOOTNOTE [1].  For the stabilization of system, i.e., so that $K_{\text{ст}}$ it

would not change the sign with the phase change, greater $\pi$, at the output of phase discriminator is placed RC-circuit.   ENDFOOTNOTE.

Noted properties of frequency self-alignment determine region of its application by those cases, when is required high frequency stability of klystron at not very high frequencies of spurious modulation, but slow frequency drift limited in value are permissible. Specifically, such conditions for application occur during the use of reflex klystron as the local oscillator in coherent-pulse radars, which ensure the selection of the moving/driving targets.

In system of ChAP spectral density of frequency fluctuations of generator at frequencies F, substantially smaller $F_{к\rho}$ can be expressed so [73]:

$$W_f(F) = \frac{W_f^0(F)}{K_{ст}^2(F)} + W_{сх}(F),        (4.2)$$

where $W_f^0(F)$ - spectral density of frequency fluctuations of nonstabilized klystron, $W_{сх}(F)$ - spectral density of frequency fluctuations, caused by noises of stabilization system.   Converting this expression, it is possible to record

$$W_f(F) = W_f^0(F)\left[\frac{1}{K_{ст}^2(0)} + \left(\frac{F}{\alpha F_{к\rho}}\right)^2\right] + W_{сх}(F),   (4.3)$$

where $\alpha \approx 1$.

Page 170.

From expression (4.3) it is evident that with F→0, when second term in brackets can be disregarded/neglected, noises of klystron

prove to be reduced to $K_{c\tau}^2$ once. With sufficiently high values of F the maximum decrease of the spectral density of the frequency fluctuations of the nonstabilized klystron is possible only $(F/F_{\kappa p})^2$ once.

As already mentioned in § 2 Chapter 3, for local oscillator in coherent-pulse radars frequency drift of 10-30 Hz are permissible during repetition period. At the repetition frequency, for example $F_n = 2000$ Hz, especially dangerous are the fluctuations of the frequency of heterodyne near half frequency $F_n$ i.e. in the range from $F_1 = 500$ Hz to $F_2 = 1500$ Hz.

Mean square of frequency fluctuations of klystron oscillator in system ChAP in the range of frequencies $F_1-F_2$ can be expressed through spectral density of frequency fluctuations

$$\overline{\delta f_{c\tau}^2} = \int_{F_1}^{F_2} W_f(F) \, dF. \tag{4.4}$$

If we assume that in necessary comparatively narrow frequency band of 500-1500 Hz $W_f(F)$ is constant/invariable, to accept $F_{\kappa p} = 10^5$ Hz [74], $K_{c\tau} = 10^2$ (which easily it can be achieved/reached), while $W_f^0 = 10 \div 100$ Hz$^2$Hz at frequency $F = 10^3$ Hz, then mean square of frequency fluctuations, caused by noises of klystron, $\overline{\delta f_{c\tau}^2} = 2-20$ Hz$^2$ and value of effective deviation of frequency $\sigma_f - \sqrt{\overline{\delta f_{c\tau}^2}} = 1.4-4.5$ Hz.

Such numeral are completely satisfactory for the local osciallator of coherent-pulse radar.

In given example noises of very stabilization system were not considered. In the real diagrams ChAP at the low frequencies (less than 5 kHz) the second term in expression (4.3) proves to be more than the first [74] and, thereby, in the region of low Doppler frequencies the frequency fluctuations of system are determined by the noises of very antihunting circuit. At the higher frequencies the frequency fluctuations of klystron, which when $F \approx F_{\text{кр}}$ approach a noise level of the nonstabilized klystron, become determining.

The presence of fluctuations of amplitude of oscillations of generator and fluctuations of circuit parameters they can cause certain increase in frequency noise at output of stabilization system.

Phase automatic frequency control (·FAP·). The block diagram of the phase automatic frequency control of reflex klystron is given fig. 4.3. Fundamental network elements are: dual waveguide tee, in one of lateral arms of which is arranged/located matched detector д; reference oscillator, which consists of crystal assigning oscillator and frequency multiplier on semiconductor diodes; IF amplifier; buffer amplifier; phase discriminator and control device/equipment.

Page 171.

On detector д is isolated signal of difference frequency of oscillations of klystron and reference oscillator, which after amplification is supplied to phase-sensitive detector. On the phase

discriminator the comparison on the phase of this signal with the

oscillations of the master oscillator is realized.  With the deviation

of the frequency of klystron relative to reference oscillator on the

phase discriminator will appear the voltage/stress, sign and value of _ _

which depend on phase displacement of the signal of difference

frequency.  The developed error signal through the control system is

supplied to the klystron repeller, reducing the value of phase

displacement of the oscillations of klystron relative to the

oscillations of supporting/reference generator to the minimum.

System FAP is in stable state with constancy of voltage/stress,

removed from phase discriminator.  This state corresponds to certain

constant phase displacement of the oscillations of klystron and

reference oscillator, which is possible only with the equality of

frequencies of these.  Thus, system FAP is the astatic with respect to

the changes frequency of klystron oscillator and provides the very

high stabilization factor of "slow" frequency drift of the

adjustable/tuneable klystron, limited virtually to the stability of

crystal oscillator.

Such properties of system FAP make its application more

preferable in comparison with system ChAP in such cases, when is

important absolute frequency stability of klystron, and when necessary

strongly to also weaken/attenuate fluctuations of oscillations of

klystron oscillator at frequencies, close to carrier.  This causes the

wide application of FAP for frequency fixing of the master oscillator

in the coherent continuous-wave radars.

In system FAP phase change in diagram, just as in system ChAP, leads to decrease of stabilization factor with increase in frequency of fluctuations. If we take measures for the stabilization of system, then $K_{cr} \to 1$ when $F \to F_{кр}$. At frequencies F, substantially smaller $F_{кр}$ $(F < F_{кр}/3)$, stabilization factor approximately can be expressed thus:

$$K_{cr} \approx \frac{\Delta f_y}{F},\qquad(4.5)$$

where $\Delta f_y$ - band of the retention of system FAP.
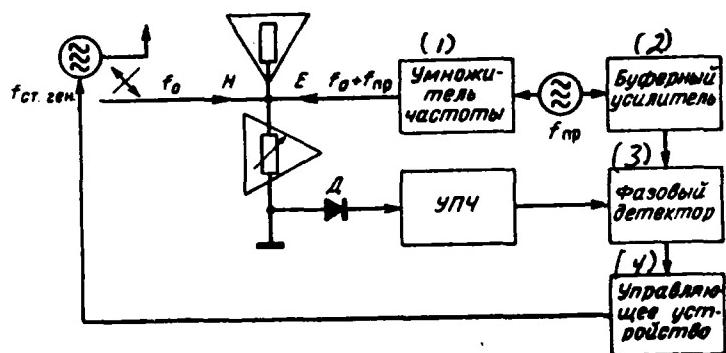
Fig. 4.3.  Diagram of phase self-alignment (FAP).

Key:  (1).  Frequency multiplier.  (2).  Buffer amplifier.  (3).

Phase discriminator.  (4).  Control system.

Page 172.

Frequency fluctuations in the system FAP can be expressed analogously

(with 4.2)

$$W_f(F) = \frac{W_f^*(F)}{K_{cr}^2(F)} + W_{cx}(F).  \tag{4.6}$$

After substituting (4.5) in (4.6), we will obtain [73]

$$W_f(F) = \frac{F^2\, W_f^0(F)}{(\Delta f_y)^2} + W_{cx}(F).  \tag{4.7}$$

From expression (4.7) it is evident that $W_f(F) \to W_{cx}(F)$ with F→0, i.e.

determining are the fluctuations of the diagrams, which, in turn, at

the very low frequencies virtually completely are caused by changes in

the frequency of reference oscillator.  With an increase in the

frequency the fluctuations of the frequencies of klystron oscillator,

which substantially exceed fluctuations caused by the instabilities of

the oscillations of reference oscillator, become determining.

With real values of band of retention FAP $(\Delta f_y \approx 10^6$ Hz) weakening frequency fluctuations of klystron at frequencies F=1-10 kHz is very considerable and relation $W_f(F)/W_f^0(F)$ composes $10^{-6}-10^{-4}$ (-60 to -40 dB).

As in system ChAP, in system FAP considerable fluctuations of amplitude of oscillations of klystron, reference oscillator and fluctuation of circuit parameters lead to increase in level of frequency fluctuations.

Analyzing systems APCh, in conclusion it is necessary to draw some general conclusions. The systems indicated possess property substantial to decrease the fluctuations of the frequency of reflex klystrons; however, in this case they have a number of the serious deficiencies/lacks, fundamental from which following:

- the presence of inertial elements/cells, which leads to considerable reduction in the value of the suppression of the frequency fluctuations of klystron with an increase in the frequency of fluctuations;

- ill effect of the amplitude fluctuations of generator and fluctuations of the circuit parameters of the level of frequency noises;

- limitedness of the possibility of the suppression of the frequency fluctuations of klystron oscillator at the low frequencies by the inherent noise level of system APCh;

- complexity of the adjustment of systems APCh and difficulty of

their retuning even in the narrow frequency band;

- difficulty of using the systems APCh for the stabilization of span klystrons, the connected with the need administrations for the electrode, which consumes considerable current.

4.2.  Frequency fixing of klystron oscillator by external high-Q resonator.

Systems of parametric frequency fixing of klystron oscillators by external high-Q resonator are to a considerable extent deprived of deficiencies/lacks, characteristic for systems APCh.  Such systems, based on the phenomenon of frequency pulling of generator with resonance load, received wide acceptance.  As the resonance load cavity high-Q resonator is utilized.

Page 173.

In S 2 it is shown that level of frequency fluctuations of klystron oscillator significantly depends on value of quality of resonance system.  It is natural that the connection with the specific shape of the external resonator of that possessing quality, many times of the larger quality of the resonance system of klystron, must lead to the decrease of the level of frequency noises.

In this paragraph is not posed the problem of complete description of properties and analysis of principles of construction of stabilization systems of klystron oscillators by external high-Q

resonator, since this exceeds the scope of this book.  The principles of the work of such systems and their effect on the level of the fluctuations of klystron oscillator will be only briefly presented. The questions, connected with calculation and construction of stabilization systems are presented in works [75- 85], the methods of engineering the stabilizing resonators - in works [80, 86].

Different circuit diagrams of external resonator and reflex klystron are possible.  Most extensively is used the circuit diagram of external resonator "to the passage" between the klystron and the load (Fig. 4.4).  In this diagram cavity high-Q resonator is connected to reflex klystron through the intermediate resonator, which is, as a rule the section of the waveguide of the specific length.  The systems stabilizing properties will be provided in such a case, when the reactive load, created by resonator with the divergence of oscillation frequency from its resonance frequency, will counteract this divergence.

This system can be considered as three-circuit, counting its own oscillatory system of klystron for one equivalent duct/contour, which is completely admissible in sufficiently narrow band of frequencies [75].  Condition, which determines oscillation frequency,

$$B + B_e = 0. \qquad (4.8)$$
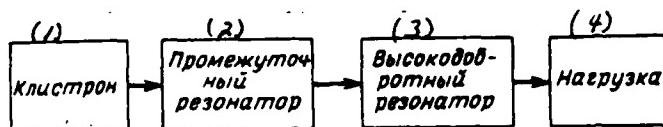
Fig. 4.4.  Block-diagram of stabilization of reflex klystron by external resonator, connected "to passage".

Key: (1).  Klystron.  (2).  Intermediate resonator.  (3).  High-Q resonator.  (4).  Load.

Page 174.

In this case of B - reactive component of the multicircuit resonance system, which consists of the equivalent duct/contour of klystron, intermediate and high-Q resonators, which in view of the high quality of external resonator is determined by the latter; $B_e$ - reactive/jet component of the electronic conductivity of klystron.

For guaranteeing necessary sign of susceptance of external resonator during its transformation from plane of equivalent inclusion of resonator into plane of high-frequency gap of klystron length of coupling section/segment must be completely specific.  In practice the length of the coupling section/segment, connected between the output collar of klystron and the input collar of resonator, is regulated with the aid of the special element/cell, placed in the coupling section/segment.

Since oscillatory system of stabilized klystron is three-circuit, in it oscillations at several frequencies are possible.  The parasitic

frequency, determined in essence by tuning/adjusting intermediate

resonator, is closest to the resonance frequency of external

resonator.  For the purpose of the suppression of spurious resonances

in the section/segment a certain attenuation with the aid of the

absorbing plate is introduced.  The introduction of the absorbing load

with the small attenuation (about 1 dB) breaks away the parasitic

oscillations, whose energy reserves itself in the intermediate

resonator and virtually does not affect the dominant mode of

oscillations, connected with the external resonator.


Like any automatic control system, stabilized by external high-Q

resonator system is characterized by ranges of retention and capture

of operating frequency with its change as a result of staggering of

klystron or voltage error of reflector from nominal value.  The work

of klystron in this system is the more stable, the less the quality of

external and intermediate resonators.


In practice identification of parameters of separate network

elements is certain compromise, since decrease of quality of external

resonator and increase of attenuation in coupling section/segment

leads to reduction in stabilization factor, but decrease of length of

section/segment is not always possible (in particular during use of

superconducting high-Q resonators, workers in cryostat with liquid

helium).


Stabilization factor is fundamental characteristics of stabilized

system.

Page 175.

The stabilization factor of frequency with drifts, the drifts/cares,
connected with a change in the resonance frequency of the oscillatory
system of klystron, disregarding by losses in the coupling
section/segment, is approximately determined (for example, into [75])
thus:

$$K_{\text{к ст}} \approx \frac{Q_{1\text{p вн}}}{Q_{\text{к вн}}}, \qquad (4.9)$$

where $Q_{1\text{p вн}}$ - external q of the stabilizing resonator from the side of
input connection/communication; $Q_{\text{к вн}}$ - external q of klystron
duct/contour.  The stabilization factor on the reflector, connected
with the frequency drift with a change in the voltage/stress on the
reflector, is equal to

$$K_{R\text{ ст}} = \frac{\partial f / \partial V_R}{(\partial f / \partial V_R)_{\text{ст}}}. \qquad (4.10)$$

Taking into account that value $\partial f / \partial V_R$ is inversely proportional to
loaded quality of oscillatory system

$$K_{R\text{ ст}} = \frac{Q_{\text{сн}}}{Q_{\text{кн}}}, \qquad (4.11)$$

where $Q_{\text{кн}}$ - loaded energy factor of klystron duct/contour; $Q_{\text{сн}}$ -
equivalent loaded quality of stabilized system.

In quotient, but close to real, case, when steady state of
stabilized klystron coincides with its mode/conditions out of
stabilization system, i.e., with equality of total conductances of
stabilized and nonstabilized klystrons, stabilization factor on

reflector (4.11) proves to be equal to stabilization factor of oscillatory system (4.9).

Fig.  4.5 depicts equivalent schematic of stabilized system, depicted in Fig. 4.4.
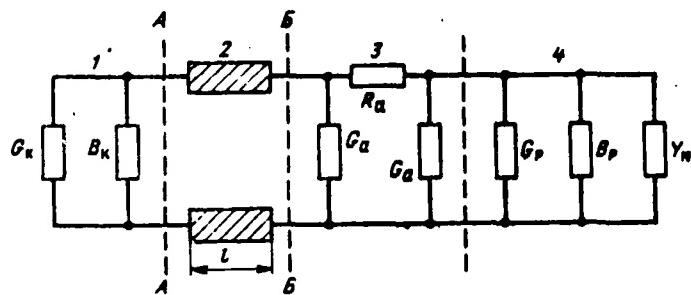
Fig. 4.5. Equivalent schematic of stabilized system, led to specific section of waveguide at output of klystron: 1 - stabilized klystron; 2, 3 - intermediate resonator with attenuator; 4 - external resonator, loaded to conductivity $Y_{\text{м}}$.

Page 176.

Equivalent diagram is reduced to the specific section of waveguide at the output of klystron. Between the sections $AA—ББ$ the attenuator in the coupling section/segment is shown.

If we consider external of resonator as that coordinated from entry side then loaded quality of this system is equal to

$$Q_{\text{сн}} = \left( \frac{Q_{1\text{р вн}}}{L_{\text{а}}} + Q_{\text{кн}} \right) \frac{1}{1 \dotplus \dfrac{1}{K_{\text{к}}}} . \qquad (4.12)$$

where $L_{\text{а}}$ - attenuation, introduced by attenuator in coupling section/segment; $K_{\text{к}}$ - parameter of agreement of klystron with load, equal KSVN [       - VSWR] in "hot" state in the case "of over/rebond and 1/KSVN - at "underbond".

In this case spectral density of frequency noises of klystron by

stabilization system is evinced

$$W_{f\,ст} = \frac{W_f''}{K_{ст}'^2} = W_f'' \frac{Q_{кн}^2}{Q_{ш}^2} \,. \qquad (4.13)$$

At present in usual stabilization systems of klystron with the aid of external high-Q resonator of comparative stabilization factors 30-100 easily are realized, which makes it possible to decrease spectral density of frequency fluctuations of nonstabilized klystron on 30-40 dB.  Comparing these systems with the diagrams of APCh, one should note that the stabilization systems by external resonator possess a number of unconditional advantages.

Since feedback in stabilization systems with the aid of external cavity resonator is realized in high frequency, then they are virtually inertia-free.  Thus, the degree of the suppression of frequency fluctuations does not depend on their frequency, and to the equal degree decrease both slow and rapid changes in the frequency. These systems possess a comparatively simple retuning of oscillation frequency, which can be achieved in the the small band of by change in resonance frequency of external resonator, and in the wider interval - by tuning also of the duct/contour of klystron and length of coupling section/segment.  In the stabilization systems of the frequency of reflection klystron by external high-Q resonator, in contrast to the systems APCh, virtually is not exerted harmful effect of the fluctuation of amplitude.

Page 177.

*A* deficiency/lack in such systems is that that prolonged
frequency stability is determined by the properties of the external
stabilizing resonator.  Even with the observance of the necessary
measures for an increase in the stability of external resonator
(production of resonator from Invar, which possesses the low
coefficient of temperature expansion, hermetic sealing/pressurization
of resonator, etc.) the prolonged relative stability of the
generatable frequency does not exceed $10^{-5}$, which is considerably
worse than the stability of klystrons in the system FAP, determined by
quartz harmonic generator.  Furthermore, stabilization with external
resonator is connected with the considerable power losses in this
resonator, which grow/rise with an increase in the stabilization
factor and with the sufficiently high values of the latter they reach
5-7 dB.

Liquidation of these deficiencies/lacks or, in any case,
essential IS weakening is possible by applying superconducting
stabilizing resonators [91, 92].  Such resonators, prepared from the
special materials and which work in liquid helium, can have our own
quality several million (for example, into [92] $Q=2\cdot10^{6}$) instead of
$2\cdot10^{3}-4\cdot10^{3}$ in usual resonators.  In this case an increase in its own
quality of external resonator due to the decrease of losses in it
makes it possible to obtain respectively high stabilization factor
with sharp reduction in the power losses for the stabilization, which
do not exceed 3-4 dB.  Furthermore, the temperature constancy of the

medium of that surrounding resonator, in conjunction with the high

stabilizing properties can ensure prolonged frequency stability

(approximately $10^{-10}$ [92]).


   Stabilization systems examined above related to reflex klystrons.

With the aid of the external high-Q resonators possibly also reduction

in the frequencies nyx fluctuations of generators on span klystrons

[87-90].  In this case different circuit diagrams of the cavity

resonator are utilized:  it can be connected with the feedback loop

either it is connected directly with the input or output circuit of

klystron.


   Level of frequency noises of stabilized generators on span

klystrons will not noticeably differ from noise level of stabilized

reflex klystrons in such a case, when as external resonators

resonators with identical qualities are used, in spite of the fact

that its own frequency fluctuations of generator on span klystron

somewhat lower than in reflex klystrons, as a result of higher energy

factor of ducts/contours of span klystrons.  This is explained by the

fact that the qualities of the stabilized systems on both types of

klystrons will be close ones to each other.

Page 178.

Each of mentioned antihunting circuits has their advantages and disadvantages. In particular, upon the inclusion of resonator into the feedback loop there are no considerable power losses, given up into the load. However, the adjustment of this diagram and the retuning of the generatable frequency somewhat more complicated than in the second case. With the connection of external resonator to one of the ducts/contours of klystron the band of retention [89] considerably becomes narrow.

Comparing different radio engineering methods of reduction in frequency noises of klystron oscillators (APCh and parametric method of stabilization), it is possible to note that they all provide considerable noise reduction in Doppler frequency band. The diagrams of the automatic frequency control, possessing at the low frequencies greater stabilization factor, than antihunting circuit by external high-Q resonator, nevertheless, in practice do not give essential gain, since the noise level in these diagrams near the fundamental signal is caused by its own fluctuations of system APCh. At the same time the uniformity of the suppression of the frequency fluctuations of klystron oscillator in entire interval of Doppler frequencies by the stabilization system by external resonator is made with their very convenient for the use in coherent radars, where the requirements for the value of signal-to-noise ratio grow/rise with an increase in the frequency. The latter is explained by the fact that with the large $F$, that correspond to high target speeds, for the effective fight with

such targets is necessary the larger time interval and, consequently, their detection at great distances is desirable, than the slowly moving/driving targets.

Thus, each of briefly analyzed methods of reduction in frequency noises of klystron oscillators has their advantages and disadvantages. The final solution about the application of one or the other antihunting circuit must be accepted on the base of the account of all factors, which encompass both the requirements for the characteristics of radar, and special features of utilized klystron oscillator.

5.  Noise characteristics of contemporary klystron oscillators of a small power.

In catalogs, advertisements and periodic literature parameters, which characterize noisiness of contemporary klystron oscillators and especially noise characteristics in frequency region, close to carrier, are published comparatively rarely.

Page 179.

Therefore appear the specific difficulties during the attempt to analyze the values of noises reached and to compare them with the design features and the modes of operation of the actual types of klystrons.

In this paragraph are given fundamental published materials,

which characterize noisiness both of reflecting, and span generator klystrons.

Table 4 gives fundamental parameters of contemporary low-noise klystron oscillators, and in Fig. 4.6 - typical spectral noise characteristics. On the spectral characteristics of frequency noises raising noise level at frequencies less than 10-20 kHz, determined by flicker effects, is distinctly visible. However, the course of some curves, reproduced by us on the basis of the appropriate sources, causes doubt. Thus, for example, the excessively sharp lift of frequency noises in stabilized reflex klystron of firm Varian at the low frequencies and the nonconformity of the course of the characteristics of stabilized and nonstabilized klystrons according to data [94] (curves 6) can be explained, probably, only by errors in the measurements.

Gridless two-cavity span klystrons possess lower level of frequency noises. These klystrons work with high voltages, which impedes their application in the small/miniature onboard equipment. during the use in the span klystrons of the grids of voltage/stress decrease, but noises increase on 10-15 dB. Thus, according to data [98], at the frequency F=30 kHz the level of the frequency noise of gridless span klystron comprises $(5-9) \cdot 10^5$ Hz$^2$/Hz, and for the span klystron with the grids it is equal to $(1-4) \times 10^{-3}$ Hz$^2$/Hz, i.e., noise level becomes close to the noise level of reflex klystrons. The lowest level of frequency noise among the span two-cavity klystrons

possesses the experimental klystron of firm Ferranti (curve 12), in which according to data [93] is increased resonator gap.

Reflection klystrons with high-Q stabilizing resonators possess level of frequency noise, to temporarily inferior best stabilized span klystrons, and therefore wide application is found, since they work with considerably lower feeding voltages. Klystrons with the increased power output possess the smallest noise level among reflex klystrons. This is connected with the work on the low numbers of the zones of generation, by the use of those increased as compared with the heterodyne klystrons of voltages/stresses, which makes it possible to use grids with the large transparency and to decrease the noises of current interception.

Page 180-181.

Table 4. Fundamental parameters of contemporary foreign low- noise klystron oscillators.

| A Обозначение | B Тип генератора | C Фирма, источник | D Раб. частота, Гги | E Напряжение резонатора, в | F Ток кат. в, ма | Напряжение отражателя, в | H Выходная мощность, мвт | I Шумовые характеристики | | | M Примечание |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | J частоты расстройки, кгц | K амплитуд- ные шумы –дб/гц | L частотные шумы, гц²/гц | |
| QK 656 | (1) Отражательный клист- рон со стабилизирую- щим резонатором | Raytheon [94] | 24 | 450 | 50 | –(300÷325) | 100 | 3–100 | 130–150 | 1÷0,05 | |
| | (2) Отражательный клист- рон | Sperry [96] | 10 | | — | — | 500 | 1–100 | | 0,1 ÷ ÷0,010 | (3 b) |
| BPC 201A | (3a) Отражательный клист- рон VA-273В со стабили- зирующим резонатором BC-1307 (4a) | Varian [96] | 10 | 750 | 80 | (400÷600) | 100 | 1,5 | 136 | 2,5·10⁻⁴ (4a) | Коэффициент стабили- зации Kст –50, крутизна электронной настройки 6,5 кгц/в (4b) |
| VA-273В | Отражательный клист- рон | Varian [96] | 10 | 750 | 80 | (400÷600) | 1 000 | 1,5 | — | 0,6 (по расчету) | Крутизна электронной настройки 2,25 Мгц/в |
| BPC 201 | (5a) Отражательный клист- рон VA-297 (или VA-273С) со стабилизи- рующим резонатором BC-1305 (6a) | Varian [96] | 10 | 750 | 80 | –(200÷600) | 50 | 0,02; 0,1; 1,0 | — | 66; 1,5; 4·10⁻³ | Коэффициент стабили- зации Kст –35; крутиз- на электронной настрой- ки 6 кгц/в (5b) |
| | Отражательный клист- рон | Varian [94] | 5,5 | — | | — | 1 000 | 1,0–100 | 150–155 | 8·10⁻⁴÷ ÷9·10⁻³ | (6b) При использовании стабилизирующего резо- натора частотный шум 5,4·10⁻⁴÷2·10⁻⁶ гц²/гц |
| QKK 1106 | (7a) Пролетный двухрезо- наторный клистрон | Raytheon [94, 97] | 10,5 | 3 900 | 25 | — | 1 500 | 2–100 | 140–160 | 4·10⁻⁴÷ ÷2·10⁻³ | Крутизна электронной настройки 4 кгц/в (7b) |
| VA-221A | (8a) Пролетный двухрезо- наторный клистрон | Varian [98, 99] | 5,5 | 4 000 | 33 | — | 2 000 | 10; 30 | 165 | 2·10⁻⁴÷ 9·10⁻³ | (9 b) |
| BPC 207 | Пролетный двухрезо- наторный клистрон VA-514 со стабилизи- рующим резонатором BC-1312 (9a) | Varian [96] | 9,3 | 4 200 | 40 | — | 500– 1 000 | 0,05–6 | — | 1,6·10⁻³ | Коэффициент стабили- зации Kст –30 |
| VA-504B | (10) Пролетный двухрезо- наторный клистрон | Varian [99] | 13,3 | 3 000 | 72 | — | 15 000 | 5 | 145 | 1,6·10⁻⁴ | |
| SZ 22 | (11) Пролетный двухрезо- наторный клистрон | Ferranti [93] | 9 | 7 000 | 30 | — | 15 000 | 1–64 | 165–180 | 8·10⁻³÷ ÷2·10⁻⁴ | |
| | (12) Пролетный двухрезо- наторный клистрон | Ferranti [93, 94] | 10 | 7 000 | 30 | — | 1 000 | 2–100 | 165–180 | 6·10⁻⁴÷ ÷2·10⁻⁴ | (13 b) При использовании |
| SOX 239 | (13a) Пролетный двухрезо- наторный клистрон | Sperry [94] | 10,6 | 3 100 | 17 | — | 2 000 | 1–100 | 140–180 | 9,3·10⁻⁴÷ ÷4·10⁻⁴ | стабилизирующего резо- натора частотный шум 9·10⁻⁴÷2,5·10⁻⁴ |
| | (14) Пролетный двухрезо- наторный клистрон со стабилизирующим резо- натором | Sperry [100] | 9,7 | | | — | 600 | 5 | 150 | 6·10⁻³ | Коэффициент стабили- зации Kст –12; потери мощности в резонаторе 10 дб (14b) |

Key: (A). Designation. (B). Type of generator. (C). Firm, source. (D). working frequency, GHz. (E). Resonator voltage, V. (F). Current of cathode mA. (G). Repeller voltage, V. (H). Power output, mW. (I). Noise characteristics. (J). frequency of detuning, kHz. (K). amplitude noises -db/Hz. (L). frequency noises, Hz²/Hz. (M). Note. (1). Reflex klystron with stabilizing

resonator. (2). Reflex klystron. (3a). Reflex klystron ... with
stabilizing resonator .... (3b). Stabilization factor ...;
slope/transconductance of electronic electronic tuning/adjusting of
5.5 kHz/v. (4a). Reflex klystron. (4b).:. (according to the
calculation) .... (4c). Slope/transconductance of electronic
tuning/adjusting of 2.25 MHz/v. (5a). Reflex klystron ... (or ...)
with the stabilizing resonator .... (5a). Reflex klystron ... (or
...) with the stabilizing resonator .... (5). Stabilization factor
...; tuning/adjusting 6 kHz/$V$. (6a). Reflex klystron. (6b). During
the use of stabilizing resonator frequency noise ... Hz²/Hz. (7a).
Span two-cavity klystron. (7b). Slope/transconductance of the
electronic tuning/adjusting of 4 kHz/$V$. (8). Span two-cavity
klystron. (9a). Span two-cavity klystron ... with the stabilizing
resonator ..... (9b). Stabilization factor .... (10). Span two-
cavity klystron. (11). Span two-cavity klystron. (12). Span
two-cavity klystron. (13a). Span two-cavity klystron. (13b).
During the use of the stabilizing resonator frequency noise ....
(14a). Span two-cavity klystron with the stabilizing resonator.
(14b). Stabilization factor ...; power loss in the resonator 10 dB.

Page 182.

Analyzing tables 4 and Fig. 4.6, it is possible to note tendency
toward deterioration in noise characteristics in proportion to
increase in operating frequency of generatable
oscillations/vibrations. Reason here lies not only in the fact that
the intensity of frequency noise is proportional to the square of

frequency of the generatable, but both in the increase of the role of

the surplus noises of different origin with the decrease of the

geometric dimensions of operating regions of klystron and also in the

increase of the difficulties of designing of optimum electron-optical

systems.
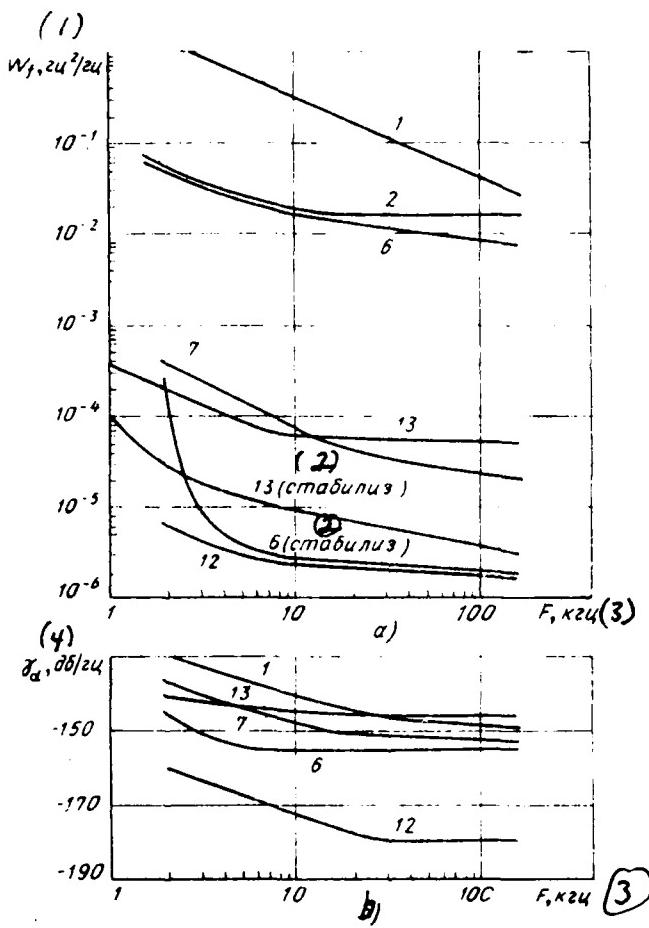
Fig. 4.6. Frequency (a) and amplitude (b) noise characteristics of contemporary klystron oscillators. The number of curve corresponds to reference number in Table 4.

Key: (1). Hz²/Hz. (2). (stabil). (3). kHz. (4). dB/Hz.

Page 183.

Appendix 1.


SOME INFORMATION FROM THE THEORY OF RANDOM PROCESSES.

General concepts and determinations.


Random processes (noises) are described by random variables,

which depend on time, i.e., by random functions of time u(t), which

express any specific parameter of generator; current, amplitude of

oscillations, frequency of oscillation/vibrations, etc.


Any random process is defined by totality of functions of time,

each of which can be obtained as result of single experiment

(measurement) and is called realization of random function.  The

totality of the set of possible realizations composes the ensemble of

the realizations ·of fluctuation process ($\mathfrak{f}$ig.  Π1).  The realization,

limited by the specific time interval, is called truncated.


At specific moment of time, for example $t_1$ (Fig.  Π1), function

$y(t_1)$ accepts possibility of random values (according to number of

realizations).  The totality of these values forms random variable.


Average/mean value (mathematical expectation) and dispersion are

important characteristics of random process.  The average/mean value

$\overline{y(t_1)}$ averaging markedly by feature on top) determines by itself the

level, relative to which are scattered possible values of random

variable at the specific moment of time. Dispersion $\sigma^2$ is the mean square of the possible divergences of random variable at the specific moment of time relative to the average/mean value of $\sigma^2 = [y(t_1) - \overline{y(t_1)}]^2$.

Random processes, whose average/mean value and dispersion do not depend on time, are stationary [1].

FOOTNOTE [1]. Stability in the broad sense [25] is intended. ENDFOOTNOTE.
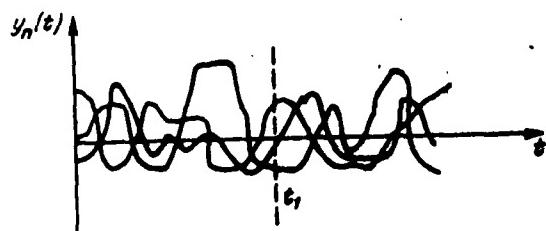
Fig. Л1.   Ensemble of the realizations of fluctuation process.

Page 184.

The stationary processes, which possess ergodic property, occupy the important place among random processes.  The latter consists in the fact that the mean statistical characteristics of such processes (for example, average/mean value and dispersion), the obtained by averaging one realizations over the time, are equal of to the values, obtained by averaging over the ensemble of realizations at the arbitrarily selected moment of time.  From the properties of ergodicity it follows that if necessary the study only of one realization for the sufficiently large interval of time instead of the study of the large totality of realizations is possible.  The following presentation concerns stationary ergodic processes.

During analysis of random processes it is convenient to represent random function in the form of sum of its average/mean value and fluctuation (divergence of its instantaneous value from average):

$$y(t) = \overline{y(t)} + \delta y(t). \qquad (1)$$

From definition of (1) it follows that $\overline{\delta y(t)} = 0$.  The value of the mean square of fluctuation $[\overline{\delta y(t)}]^2$ (i.e. dispersion) determines the

intensity of fluctuations.

ENERGY SPECTRUM OF FLUCTUATION PROCESS.

Any noncyclic function y(t) [if it is continuous, with exception of finite number of points of discontinuities, and there is integral $\int_{-\infty}^{+\infty} |y(t)|\,dt$; it can be represented by integral of Fourier

$$y(t) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} \dot{y}(\omega)e^{j\omega t}\,d\omega .\qquad(2)$$

This expression gives the expansion of time function y(t) into the spectrum with complex amplitudes of $\frac{y(\omega)d\omega}{2\pi}$. moreover $\dot{y}(\omega)$ is called the spectral function or the spectrum of function y(t).  In turn,

$$\dot{y}(\omega) = \int_{-\infty}^{+\infty} y(t)e^{-j\omega t}\,dt ,\qquad(3)$$

which expresses Fourier transform.

Mathematical method indicated is applicable for harmonic analysis of random processes, although for random function y(t) integral $\int_{-\infty}^{+\infty} |y(t)|\,dt$ does not exist.  Let us examine the n-th realization $y_n(t)$ of stationary periodic process with the zero average/mean value in the range of time from   -T/2 to +T/2 (truncated realization), considering that out of this interval it is equal to zero.

Page 185.

For this case are completely applicable expressions (2) and (3). If   $y_n(t)$ - voltage/stress or current on the load into 1 ohm, then total energy of fluctuation process is expressed as the modulus/module

of spectral function as follows:

$$\int_{-\infty}^{+\infty} [y_n(t)]^2 \, dt = \frac{1}{\pi} \int_{0}^{\infty} |\dot{y}_n(\omega)|^2 \, d\omega. \qquad (4)$$

After dividing entire energy of process to period of its action T, we will obtain

$$\frac{1}{T} \int_{-\infty}^{+\infty} [y_n(t)]^2 \, dt = \frac{1}{\pi T} \int_{0}^{\infty} |\dot{y}_n(\omega)|^2 \, d\omega = \frac{2}{T} \int_{0}^{\infty} |\dot{y}_n(f)|^2 \, df. \qquad (5)$$

This expression determines mean power of the truncated realization of fluctuation process and it can be rewritten in the following form:

$$P = \int_{0}^{\infty} W_{Tn}(f) \, df, \qquad (6)$$

where $W_{Tn}(f) = \frac{2}{T} |\dot{y}_n(f)|^2$ - spectral power density of the truncated realization of fluctuation process referred to the frequency, expressed in hertz.

Strict analysis shows that when $T \to \infty$ $W_{Tn}(f)$, remaining final, does not strive toward specific limit. However, after averaging preliminarily $W_{Tn}(f)$ over the ensemble of the realizations (let us designate this operation/process by wavy line), it is possible to obtain expression for the spectral power density of random process and under these conditions:

$$W(f) = \lim_{T \to \infty} \widetilde{W_{Tn}(f)} = \lim_{T \to \infty} \frac{2}{T} \widetilde{|\dot{y}_n(\omega)|^2}. \qquad (7)$$

Value $W(f)$, besides spectral power density, is frequently called spectral density of mean square or energy spectrum of random process (fluctuation). Thus, knowing expression for the spectral density it is possible to find the power of fluctuation process, which is

isolated in the specific band of frequencies Δf:

$$\{\overline{[y(t)]^2}\}_{\Delta f} = \int\limits_{f}^{f+\Delta f} W(f)\,df. \qquad (8)$$

If in the band of frequencies Δf value $W(f) \approx \text{const}$, then

$$\{\overline{[y(t)]^2}\}_{\Delta f} \approx W(f_0)\,\Delta f. \qquad (9)$$

According to form of spectrum random processes are subdivided into broadband, width of spectrum of which much more than their medium frequency, and narrow-band with width of spectrum of small in comparison with medium frequency.

Page 186.

If sum of independent random processes $y(t)=y_1(t)+y_2(t)+y_3(t)+...$ is examined, then energy spectrum of process y(t) is equal to sum of energy spectra of the components: $W_y(f) = W_{y_1}(f) + W_{y_2}(f) + W_{y_3}(f) + \cdots$   If processes $y_1(t)$, $y_2(t)$ and so forth are interrelated (partially or are completely correlated), total energy spectrum is not equal to the sum of the spectra of each of the processes. Thus, for example, for the sum of two correlated random processes $y_1(t)$ and $y(_2(t)$ we will obtain where

$$W_y(f) = W_{y_1}(f) + W_{y_2}(f) + W_{y_1 y_2}(f) + W_{y_2 y_1}(f), \qquad (10)$$

$$W_{y_1 y_2}(f) = W^*_{y_2 y_1}(f) = \lim_{T \to \infty} \frac{2}{T}[\dot{y}_2(f)y^*_1(f)]$$

– mutual energy spectrum of processes $y_1(t)$ and y(t).

Let us note that in contrast to its own energy spectra, which are real functions of frequency, mutual energy spectra - complex functions of frequency (the symbol "*" it indicates complex coupling).

# FLUCTUATION PROCESS AS OSCILLATION WITH SLOWLY CHANGING BY AMPLITUDE AND PHASE.

With narrow-band process fluctuation oscillations can be harmonic oscillations, modulated on amplitude and phase. This makes it possible to record narrow-band random process in the form

$$y(t) = C(t)\cos[\omega_0 t - \varphi(t)] = a(t)\cos \omega_0 t + b(t)\sin \omega_0 t, \quad (11)$$

where $\omega_0$ - the medium frequency of the spectrum of process $y(t)$, and $C(t)$ and $\varphi(t)$ [and respectively $a(t)=C(t)\cos\varphi(t)$ and $b(t)=C(t)\sin\varphi(t)$] - slowly changing random functions of time.

This representation of fluctuation process in number of cases is very useful. Between the energy spectra of process $y(t)$ and processes $a(t)$ and $b(t)$ there is a connection/communication:

$$W_a(F) = W_b(F) = W_y(f_0 - F) + W_y(f_0 + F), \quad (12)$$

moreover

$$W_{ab}(F) = 0.$$

Appendix 2.

Tables of the parameters, utilized for describing the spectral characteristics of fluctuations.

Table П1-П3 gives definitions and conversion formulas for fundamental spectral parameters of fluctuations. Tables are handled due to the absence of the conventional system of the representation of data and the steady unified terminology. Besides the complete designation of each parameter the abbreviated/reduced versions, which are encountered in the technical literature, are given.

Page 187-188.

**Table П1.** Parameters, which describe the spectral characteristics of the fluctuations of amplitude.

| № п/п | *A* Наименование параметра | *B* Математическое определение | *C* Размер-ность | *D* Примечание |
|---|---|---|---|---|
| 1 | *(1a)* Энергетический спектр (спектральная плотность среднего квадрата) относительных флуктуаций амплитуды. <br> *(1b)* Сокращенно: <br> a) энергетический спектр флуктуаций амплитуды; <br> b) спектральная плотность флуктуаций амплитуды; <br> c) энергетический спектр амплитудного шума; <br> d) спектральная плотность амплитудного шума | $$W_a(F) = \lim_{T \to \infty} \frac{2}{T} |\overline{a_n(F)}|^2,$$ *(1c)* $$\text{где } a_n(F) = \int_{-\infty}^{+\infty} a_n(t) e^{-j2\pi Ft} dt -$$ — спектральная функция $n$-й усеченной реализации относительной флуктуации амплитуды $$a_n(t) = \frac{\delta U_n(t)}{U},$$ заданной в интервале $$-\frac{T}{2} \leqslant t < \frac{T}{2}$$ | *(1d)* $$\frac{1}{гц}$$ | |
| 2 | *(2a)* Средний квадрат относительных флуктуаций амплитуды в полосе частот $\Delta F$. <br> Сокращенно: *(2b)* <br> a) уровень флуктуаций амплитуды в полосе $\Delta F$; <br> b) уровень амплитудного шума в полосе $\Delta F$ | $$\overline{[a(t)]^2_{\Delta F}} = \int_{F}^{F+\Delta F} W_a(F) dF \approx$$ $$\approx W_a(F) \Delta F.$$ | *(2c)* Безраз-мерный пара-метр | *(2d)* Это соотношение используется при экспериментальном определении $W_a(F)$ по результату измерения $\overline{[a(t)]^2_{\Delta F}}$ в полосе пропускания анализатора спектра $\Delta F = \Delta F_c$: $$W_a(F) \approx \frac{\overline{[a(t)]^2_{\Delta F_c}}}{\Delta F.}$$ |
| 3 | *(3a)* Отношение мощности спектральных составляющих амплитудного шума в одной боковой полосе шириной $\Delta F$ (на расстоянии $F$ от средней частоты спектра колебания) к средней мощности колебания. <br> *(3b)* Сокращенно: <br> a) отношение мощности амплитудного шума в боковой полосе $\Delta F$ к мощности несущей; <br> b) отношение шум/сигнал | $$[\gamma_a(F)]_{\Delta F} = \frac{[P_{ба}]_{\Delta F}}{P_0} =$$ $$= \frac{1}{2} \int_{F}^{F+\Delta F} W_a(F) dF \approx \frac{W_a(F)\Delta F}{2}$$ *(3c)* или в децибелах: $$\{[\gamma_a(F)]_{\Delta F}\}_{[дб]} = 10 \lg \left\{ \frac{W_a(F)\Delta F}{2} \right\}.$$ | *(3d)* Безраз-мерный пара-метр | *(3e)* a) В некоторых работах используется отношение мощности амплитудного шума в двух (симметрично расположенных) боковых полосах к мощности несущей. Математическое определение в этом случае полностью совпадает с определением уровня амплитудного шума (п. 2): $$\frac{[P_{ба}]_{2\Delta F}}{P_0} = \frac{2[P_{ба}]_{\Delta F}}{P_0} \approx W_a(F)\Delta F;$$ b) Можно встретить также работы, в которых используется обратное отношение $\frac{P_0}{[P_{ба}]_{\Delta F}}$. В иностранной литературе это отношение обозначается символом $c/N$ ($\frac{carrier}{noise}$ — $\frac{несущая}{шум}$). При этом указывается вид шума (амплитудный, частотный) и оговаривается полоса $\Delta F$ |

Key:  (A) the designation of the parameter.  (B).  Mathematical
determination. (C).  Dimensionality.  (D).  Note.  (1a).  Energy
spectrum (spectral density of mean square) of relative fluctuations of
amplitude.  (1B).  In abbreviated form:  a) energy spectrum of
fluctuations of amplitude; b) spectral density of fluctuations of
amplitude; c) energy spectrum of amplitude noise; d) spectral density
of amplitude noise.  (1c).  ... where ... - spectral function of n
truncated realization of relative fluctuation in amplitude ...,
assigned in interval ....  (1d).  1/Hz.  (2a).  Mean square of
relative fluctuations of amplitude in band of frequencies $\Delta F$.  (2b).
In abbreviated form:  a) level of fluctuations of amplitude in band
$\Delta F$; b) level of amplitude noise in band $\Delta F$.  (2c).  Dimensionless
parameter.  (2d).  This relationship/ratio is utilized during
experimental determination ... from result of measurement ... in
passband of spectrum analyzer ....  (3a).  Ratio of power of spectral
components of amplitude noise in one sideband with width of $\Delta F$ (at a
distance of F from medium frequency of oscillation spectrum) to
average/mean power of oscillation.  (3b).  In abbreviated form:  a)
ratio of power of amplitude noise in sideband $\Delta F$ to carrier output; b)
relation noise/signal.  (3c).  ... or in decibels:  ....  (3d).
Dimensionless parameter.  (3e).  a) in some works is utilized the
ratio of the power of amplitude noise in two (symmetrically
arranged/located) lateral bands to the carrier output.  Mathematical
determination in this case completely coincides with the determination
of the level of amplitude noise ( p. 2);  ... b) it is possible to

meet also the works, in which is utilized inverse relation .... In the foreign literature this relation is designated by symbol c/N (carrier/noise - carrier/noise). In this case the form of noise (amplitude frequency) is indicated and band $\Delta F$ is specified.

Page 189-190.

Table П2.    Parameters, which describe the spectral characteristics of the fluctuations of frequency.

| № п/п | A Наименование параметра | B Математическое определение | C Размерность | D Примечание |
|---|---|---|---|---|
| 1 | (1a) Энергетический спектр (спектральная плотность среднего квадрата) флуктуаций частоты. (1b) Сокращенно: а) энергетический спектр флуктуаций частоты; б) спектральная плотность флуктуаций частоты; в) энергетический спектр частотного шума; г) спектральная плотность частотного шума | (1c) $$W_f(F) = \lim_{T\to\infty} \frac{2}{T} \mid \widetilde{\delta f_n(F)} \mid^2.$$ где $\delta \dot f_n(F) = \int_{-\infty}^{+\infty} \delta f_n(t)\, e^{-j2\pi F t}\, dt$ — спектральная функция $n$-й усеченной реализации флуктуации частоты $\delta f_n(t)$, заданной в интервале $$-\frac{T}{2} < t < \frac{T}{2}$$ | (1d) $\frac{\text{гц}^2}{\text{гц}}$ (1e) (гц) | (1f) В некоторых (преимущественно теоретических) работах пользуются понятием энергетического спектра флуктуаций $v(t) = 2\pi\delta f(t)$: $$W_v(F) = (2\pi)^2 W_f(F)$$ |
| 2 | Средний квадрат флуктуаций частоты в полосе частот $\Delta F$. (2a) Сокращенно (2b) а) уровень флуктуаций частоты в полосе $\Delta F$; б) уровень частотного шума в полосе $\Delta F$ | (2c) $$\overline{[\delta f(t)]^2_{\Delta F}} = \int_F^{F+\Delta F} W_f(F)\,dF \approx W_f(F)\,\Delta F$$ | (2c) $\text{гц}^2$ | (2d) Это соотношение используется при экспериментальном определении $W_f(F)$ по результату измерения $\overline{[\delta f(t)]^2_{\Delta F}}$ в полосе пропускания анализатора спектра $\Delta F = \Delta F_c$ $$W_f(F) = \frac{\overline{[\delta f(t)]^2_{\Delta F_c}}}{\Delta F_c}$$ |
| 3 | Стандартное отклонение флуктуаций частоты в полосе частот $\Delta F$ (3a) | (3a) $$[\sigma_f(F)]_{\Delta F} = \sqrt{\overline{[\delta f(t)]^2_{\Delta F}}} \approx$$ $$\approx \sqrt{W_f(F)\,\Delta F}$$ | (3b) (3c) гц | (3c) Параметр $\sigma_f(F)$ используется преимущественно в иностранной литературе. Он обозначается там «rms» (сокращение английского термина «среднеквадратичная величина») |
| 4 | (4a) Отношение мощности спектральных составляющих частотного шума в одной боковой полосе шириной $\Delta F$ на расстоянии $F$ от средней частоты спектра колебания к средней мощности колебания. Сокращенно: (4b) а) отношение мощности частотного шума в боковой полосе $\Delta F$ к мощности несущей; б) отношение шум/сигнал | $$[\gamma_f(F)]_{\Delta F} = \frac{[P_{\delta f}]_{\Delta F}}{P_0} =$$ $$= \frac{1}{2}\int_F^{F+\Delta F} \frac{W_f(F)}{F^2}\,dF \approx \frac{W_f(F)\,\Delta F}{2F^2}$$ (4c) или в децибелах: $$[[\gamma_f(F)]_{\Delta F}]_{д\delta} = 10\,\lg\left\{\frac{W_f(F)\,\Delta F}{2F^2}\right\} =$$ $$= 20\,\lg\left\{\frac{\sigma_f(F)}{\sqrt{2}\,F}\right\}.$$ | (4d) Безразмерный параметр | (4e) а) Формула применима только к крыльям спектральной линии, т. е. при $F \gg \Delta F_{\text{спектр}}$, где $\Delta F$ спектр — ширина спектральной линии. Если это условие нарушено, то $\frac{W_f(F)\,\Delta F}{2F^2}$ нельзя интерпретировать как отношение мощности частотного шума к мощности несущей. (4f) Функцию $\frac{W_f(F)}{F^2}$ можно рассматривать как энергетический спектр флуктуаций фазы (см. § 1.1 гл. 2); б) В некоторых работах используется отношение мощности частотного шума в двух симметрично расположенных боковых полосах к мощности несущей: $$\frac{[P_{\delta f}]_{2\Delta F}}{P_0} \approx \frac{2[P_{\delta f}]_{\Delta F}}{P_0} \approx \frac{W_f(F)\,\Delta F}{F^2};$$ в) Встречаются случаи использования обратного отношения: $$P_0 [P_{\delta f}]_{\Delta F}$$ (см. примечание 6 к п. 3 табл. 1). |

Key:  (A).  Designation of the parameter.  (B).  Mathematical
determination.  (C).  Dimensionality.  (D).  Note.  (1a).  Energy
spectrum (spectral density of mean square) of fluctuations of
frequency.  (1B).  In abbreviated form:  a) energy spectrum of
fluctuations in frequency; b) spectral density of fluctuations of
frequency; c) energy spectrum of frequency noise; d) spectral density
of frequency noise.  (1c).  ... where ... - spectral function of n
truncated realization of fluctuation of frequency ..., assigned in
interval ....  (1d).  Hz²/Hz.  (1e).  (Hz).  (1f).  In some
(predominantly theoretical) works they use the concept of the energy
spectrum of fluctuations ....  (2a).  Mean square of fluctuations of
frequency in band of frequencies ΔF.  (2b).  In abbreviated form:  a)
level of fluctuations of frequency in band ΔF; b) level of
fluctuations of frequency in band ΔF.  (2c).  Hz².  (2d).  This
relationship/ratio is utilized during experimental determination ...
from result of measurement ... in passband of spectrum analyzer ....
(3a).  Standard deviation of fluctuations of frequency in band of
frequencies ΔF.  (3b).  Hz.  (3c).  Parameter ... is utilized
predominantly in foreign literature.  It is designated there "rms"
(shortening English term "root-mean-square value").  (4a).  Ratio of
power of spectral components of frequency noise in one sideband with
width of ΔF at a distance of F from medium frequency of oscillation
spectrum to average/mean power of oscillation.  (4b).  In abbreviated
form:  a) ratio of power of frequency noise in sideband ΔF to carrier
output; b) relation noise/signal.  (4c).  ... or in decibels:  ....

(4d). Dimensionless parameter. (4e). a) formula is applicable only to the wings of spectral line, i.e., with ..., where $\Delta F$ the spectrum is is 0 spectral line width. If this condition is disrupted, then ... it cannot be interpreted as the ratio of the power of frequency noise to the carrier output. (4f). Function:. can be considered as the energy spectrum of the fluctuations of phase (see § 1.1 Chapters 2); b) in some works are utilized the ratio of the power of frequency noise in two symmetrically arranged/located sidebands to the carrier output: ... c) are encountered the cases of using the inverse relation: ... (see note by 6 to p. 3 of Table 1).

Page 191-192.

Table П3.  The parameters, are used for describing the spectral characteristics of noise currents in the electronic devices.

| № п/п | (A) Наименование параметра | (B) Математическое определение | (C) Размерность | (D) Примечание |
|---|---|---|---|---|
| 1 | (1a) Энергетический спектр (спектральная плотность среднего квадрата) шумового тока (флуктуаций тока) | $(1a)\ W_i(F) = \lim_{T \to \infty} \frac{2}{T} \|\delta i_n(F)\|^2$, где $\delta i_n(F) =$ $(1b) = \int_{-\infty}^{+\infty} \delta I_n(t)\, e^{-j2\pi Ft}\, dt$ — спектральная функция $n$-й усеченной реализации флуктуации тока $\delta I_n(t)$, заданной в интервале $-\frac{T}{2} < t < \frac{T}{2}$ | (1c) $\frac{a^2}{\text{Гц}}$ | |
| 2 | (2a) Безразмерный энергетический спектр шумового тока | $(2b)\ W_i'(F) = \frac{W_i(F)}{2e I_0}$, где $2eI_0$ — энергетический спектр полного дробового шума ($e$ — заряд электрона; $I_0$ — среднее значение тока, флуктуации которого изучаются). | (2c) Безразмерный параметр | (2d) Использование этого параметра имеет то преимущество, что результаты, представленные на графиках или в таблицах, легко соизмеряются с характеристическим уровнем — уровнем полного дробового шума, для которого $W_i'(F) = 1$. |
| 3 | (3a) Средний ток эквивалентного по шуму насыщенного диода Сокращенно: (3b) ток эквивалентного насыщенного диода | $(3c)\ I_9(F) = \frac{W_i(F)}{2e} = W_i'(F) I_0$. ($e$ — заряд электрона) | а | (3d) Преимущества, отмеченные в примечании к п. 2, распространяются и на параметр $I_9(F)$, для которого характеристическим уровнем (соответствующим полному дробовому шуму) является уровень $I_9(F) = I_0$. |
| 4 | (4a) Уровень шумового тока (флуктуаций тока) в полосе $\Delta F$ | $\overline{[\delta I(t)]}^2_{\Delta F} = \int_F^{F+\Delta F} W_i'(F)\, dF \approx W_i'(F)\, \Delta F$ | $a^2$ | (4b) Это соотношение используется при экспериментальном определении $W_i'(F)$ по результату измерения $\overline{[\delta I(t)]}^2_{\Delta F}$ в полосе пропускания анализатора спектра $\Delta F = \Delta F_c$: $W_i(F) \approx \frac{\overline{[\delta I(t)]}^2_{\Delta F_c}}{\Delta F_c}$ |

Key:  (A).  Designation of the parameter.  (B).  Mathematical determination.  (C).  Dimensionality.  (D).  Note.  (1a).  Energy spectrum (spectral density of mean square) of noise current (fluctuations of current).  (1B).  ... - spectral function of n truncated realization of fluctuation of current ..., assigned in

interval .... (1c). Ga²/Hz². (2a). Dimensionless energy spectrum of noise current. (2b). ... where $2eI_0$ - energy spectrum of complete shot noise (e - electron charge; $I_0$ - average current, whose fluctuations are studied). (2c). Dimensionless parameter. (2d). Use of this parameter has the advantage that results, represented on graphs/curves or in tables, easily are commensurate with characteristic level - level of complete shot noise, for which .... (3a). Average/mean current of equivalent on noise saturated diode. (3b). In abbreviated form: current of equivalent saturated diode. (3c). (e - electron charge). (3d). Advantages, noted in note to p. 2, are propagated also to parameter ..., for which characteristic level (corresponding to complete shot noise) is level .... (4a). Level of noise current (fluctuations of current) in band $\Delta F$. (4b). This relationship/ratio is utilized during experimental determination ... from result of measurement ... in passband of spectrum analyzer ....

Page 193.

In formulas, placed in tables, wavy line on top designates averaging over set, and straight line - on time. All given in the tables determinations assume the statistical stability of fluctuations.

With use of conversion formulas it is necessary to have in mind that in this book is accepted "physical" determination of energy spectrum, with which it is assigned on positive semi-axis of

frequencies and corresponds to specific power of fluctuations, which falls to infinitesimally narrow interval of usual (not angular) frequencies. During the use of other determinations of energy spectrum in the conversion formulas the coefficients will change. Thus, for example, energy spectrum it is possible to determine on the entire axis of frequencies and to relate it to the angular frequency:

$$S_a(\Omega) = \lim_{T \to \infty} \frac{1}{2\pi T} \overline{|\dot{a}_n(\Omega)|^2},$$

where $\dot{a}_n(\Omega) = \int_{-\infty}^{+\infty} a_n(t) e^{-j\omega t} dt$ – the spectral function of the truncated realization of fluctuation $a_n(t)$, assigned in the interval $- T/2 \le t \le T/2$. This determination of energy spectrum is used, in particular, into [46].


Comparing this formula with definition, accepted here (graph/count 1 Table Π1), we see that $W_a(F) = 4\pi S_a(\Omega)$. In order to arrive at the accurate result, it is necessary not simply replace in the conversion formulas, represented in the table, $W_a(F)$ by $S_a(\Omega)$, but to substitute in them $4\pi S_a(\Omega)$ for $W_a(F)$.

Page 194.

REFERENCES.

1. «Клистроны». Пер. с англ., под ред. Е. Д. Науменко. Изд-во «Советское радио», 1952.

2. «Отражательные клистроны». Пер. с англ., под ред. Е. Д. Науменко. Изд-во «Советское радио», 1954.

3. Петров Д. М. О крутизне электронной настройки отражательного клистрона. «Вопросы радиоэлектроники», сер. 1, Электроника, 1959, вып. 3, стр. 3.

4. Кукарин С. В. Современное состояние и тенденции развития приборов СВЧ. Изд-во «Советское радио», 1962.

5. Коваленко В. Ф. Введение в электронику сверхвысоких частот. Изд-во «Советское радио», 1955.

6. Watkins D. A. Noise at the potential minimum in the highfrequency diode. J. Appl. Phys., 1955, v. 26, p. 622.

7. Thompson B. J., North D. O., Harris W. A. Fluctuation in space charge limited currents at moderately high frequences. RCA Rev., 1941, v. 5, № 5, p. 371.

8. Ван-дер-Зил А. Флуктуации в радиотехнике и физике. Пер. с англ., под ред. Л. С. Гуткина. Госэнергоиздат, 1958.

9. Корнилов С. А. Низкочастотный модуляционный шум в пролетном клистроне. «Радиотехника и электроника», 1963, т. 8, № 11, стр. 1881.

10. Beam W. R. Interception noise in electron beams at microwave frequences. RCA Rev., 1955, v. 16, p. 551.

11. «Шумы в электронных приборах», под ред. Л. Д. Смуллина и А. Г. Хауса. Пер. с англ., под ред. Палатова К. И. Изд-во «Энергия», 1964.

12. Корнилов С. А. Вторично-эмиссионная электронная проводимость сетчатых зазоров. «Радиотехника и электроника», 1967, т. 12, № 8, стр. 1415.

13. Амирян Р. А. Фликкер-шум оксидного термокатода. «Радиотехника и электроника», 1969, т. 14, № 11, стр. 2036.

14. Schwantes R. C., Van-der-ziel A. Flicker noise in triodes with positive grid. Physica, 1960, v. 26, № 12, p. 1143.

15. Schwantes R. C., Van-der-ziel A. Secondary emission flicker noise. Physica, 1960, v. 26, № 12, p. 1162.

16. Шевчик В. Н., Шведов Г. Н., Соболева А. В. Волновые и колебательные явления в электронных потоках на сверхвысоких частотах. Изд-во Саратовского университета, 1962.

17. Haus D. A. Noise in one — dimensional electron beams. J. Appl. Phys., 1955, v. 26, № 5, p. 560.

18. Siegman A. E., Watkins D. A., Hsung — Cheng Hsieh. Density-function calculation of noise propagation on an multivelocity electron beam. J. Appl. Phys., 1957, v. 28, № 10, p. 1138.

19. Николаев А. А. Шумы в минимуме потенциала на СВЧ. «Вопросы радиоэлектроники», сер. 1, Электроника, 1960, вып. 9, стр. 3—17.

20. Карнаух О. И., Местечкин Я. И., Петров Д. М. Высокочастотные шумы электронной пушки. «Электронная техника», сер. 1, Электроника СВЧ, 1966, вып. 9, стр. 80—84.

21. Beam W. R. Noise wave exitation at the cathode of a microwave beam amplifier. Trans. IRE (PGED), 1957, v. ED-4, № 3, p. 226.

22. Ashkin A., White L. D. Partition noise in electron beams at microwave frequences. J. Appl. Phys., 1960, v. 31, № 8, p. 1351.

Page 195.

23. Гильманов Г. И., Николаев А. А. Распространение дробовых возмущений в ускоряемых многоскоростных потоках. «Электронная техника», сер. 1, Электроника СВЧ, 1967, вып. 3, стр. 48—58.

24. Петров Д. М. Чувствительность частоты отражательного клистрона к изменению плотности тока, «Вопросы радиоэлектроники», сер. 1, Электроника, 1959, вып. 3, стр. 25—32.

25. Левин Б. Р. Теоретические основы статистической радиотехники, книга первая. Изд-во «Советское радио», 1966.

26. Корнилов С. А. Зависимость амплитудных и частотных шумов отражательного клистрона от его режима. «Радиотехника и электроника», 1966, т. 11, № 11, стр. 2080.

27. Корнилов С. А., Кулаков А. В., Островский Ю. В. Экспериментальное исследование флуктуаций в отражательных клистронах. «Электронная техника», сер. 1, Электроника СВЧ, 1969, вып. 1, стр. 45—57.

28. Корнилов С. А., Усыченко В. Г. Влияние фликкер-эффекта на флуктуации частоты отражательного клистрона, ЖТФ, 1967, т. 36, № 9, стр. 1691.

29. Гонткевич В. С. Собственные колебания пластинок и оболочек. Изд-во «Наукова думка», 1964.

30. Петров Д. М. Расчет отражательного клистрона для режима оптимального к. п. д. «Электроника», 1959, № 3, стр. 45—62.

31. Лопин М. И., Новоселец В. И. Основные факторы, определяющие стабильность частоты и уровень шумов двухконтурных клистронных генераторов. «Электронная техника», сер. 1, Электроника СВЧ, 1968, вып. 12, стр. 49.

32. Коваленко В. Ф. Скорость испарения и давление пара химических элементов, «Электронная техника», сер. 1, Электроника СВЧ, 1969, вып. 10, стр. 119—145.

33. Гвоздовер С. Д., Слудский В. Н. О возникновении колебаний релаксационного типа в электронных пушках. «Вестник МГУ», сер. физико-матем. и естеств. наук, 1956, № 2.

34. Новоселец В. И. Исследование флуктуаций амплитуды и частоты колебаний ЛОВ типа О. «Вопросы радиоэлектроники», сер. 1. Электроника, 1960, вып. 6, стр. 23—40.

35. Tonks L., Langmuir I. Oscillation in ionized gases. Phys. Rev., 1929, v. 33, № 2, p. 195—210.

36. Hernqvist K. G. Plasma ion oscillations in electron beams. Appl., Phus., 1955, v. 26, № 5, p. 544—548.

37. Pierce J. R. Possible fluctuations in electron beams due to ions. J. Appl. Phys., 1948, v. 19, № 3, p. 231—236.

38. Waters W. E. Observations on ion oscillations in a cylindrical — beam tetrode under hard vacuum conditions. IRE Trans., 1954, v. ED-1, p. 216—220.

39. Jepsen R. L. Ion oscillation in electron beam tubes; ion motion and energy transfer. Proc. IRE, 1957, v. 45, № 8, p. 1069—1080.

40. Габович М. Д., Кириченко Г. С. Осцилляция ионов в области минимума потенциала и низкочастотные колебания в газовом разряде. ЖТФ, 1962, том XXXII, вып. 11, стр. 1376—1381.

41. Cutler C. C. Spurious modulation of electron beams. Proc. IRE, 1956, v. 44, № 1, p. 61—64.

42. Крофорд Ф. В., Киноу Г. С. Колебания и шумы в разрядах постоянного тока при низких давлениях. ТИРИ, 1961, т. 49, № 12, стр. 2045—2068.

43. Корнилов Е. А. и др. В сб. «Физика плазмы и проблемы управляемого термоядерного синтеза». Изд-во «Наукова думка», 1965, стр. 24—35.

Page 196.

44. Кертис В. Р. Открытие электростатических звуковых волн в плазме генераторных клистронов. ТИИЭР, 1967, т. 55, № 1, стр. 125—126.

45. Alexeff I., Jones W. D., Montgomery D. Controlled landau damping of ion — acoustic waves. Phys. Rev. Letters, 1967, v. 19, № 8, p. 422—425.

46. Малахов А. Н. Флуктуации в автоколебательных системах. Изд-во «Наука», 1968.

47. Берштейн И. Л. Флуктуации амплитуды и фазы лампового генератора. «Известия АН СССР», 1950, серия физическая, т .14, № 2.

48. Ахманов С. А., Ештокин В. Н., Марченко В. Ф. К методике измерения спектров флуктуаций частоты генераторов СВЧ. «Радиотехника и электроника», 1962, т. 7, № 12, стр. 2024.

49. Малахов А. Н., Николаев В. Н., Разина Т. Д. О некоторых методах и результатах измерения флуктуаций амплитуды и частоты колебаний генераторов. «Известия вузов», Радиофизика, 1961, т. 4, № 6, стр. 1065.

50. Калина В. Г., Ештокин В. Н. К расчету наименьшей неискаженной модуляции сигнала. «Вопросы радиоэлектроники», сер. 1, Электроника, 1965, вып. 9, стр. 45—53.

51. Каратецкий С. С. Об измерении паразитной шумовой модуляции микроволновых генераторов. Научно-информационный бюллетень ЛПИ им. М. И. Калинина, 1961, № 1, стр. 108.

52. Каратецкий С. С., Корнилов С. А., Хацкевич Е. И. Возможности когерентного метода измерения низкочастотных флуктуаций маломощных СВЧ генераторов. «Радиотехника», 1963, т. 18, № 6, стр. 62.

53. Корнилов С. А. Сравнение методов измерения амплитудных флуктуаций СВЧ приборов. «Вопросы радиоэлектроники», сер. 1, Электроника, 1965, вып. 9, стр. 101—119.

54. Скабовский М. С., Чугуева В. И. Экспериментальное исследование флуктуаций коэффициента передачи кристаллического смесителя. «Радиотехника и электроника», 1964, т. 9, № 3, стр. 546

55. Аптэк Ю. Э., Лебедев А. В. Предельные технические возможности измерения флуктуаций фазы (частоты) генераторов дискриминаторами СВЧ. «Известия вузов», Радиофизика, 1966, т. 9, № 3, стр. 608.

56. Скабовский М. С. Супергетеродинная схема измерения флуктуаций колебаний СВЧ. «Радиотехника и электроника», 1964, т. 9, № 3, стр. 434.

57. Whitwell A., Williams N. A new microwave technique for determining noise spectra at frequencies close to the carrier. Microwave J., 1959, November, p. 27.

58. Сколник М. Введение в технику радиолокационных систем. Пер. с англ., под ред. К. Н. Трофимова. Изд-во «Мир», 1965.

59. Крейнгель И. С. Шумовые параметры радиоприемных устройств. Изд-во «Энергия», 1969.

60. Бакулев П. А. Радиолокация движущихся целей. Изд-во «Советское радио», 1964.

61. Лисон, Джонсон. Кратковременная стабильность частоты допплеровских радиолокационных станций: требования, измерения, методы. ТИИЭР, 1966, т. 54, № 2, стр. 157.

62. Бунин Г. Г., Киянов Е. П. Анализ влияния нестабильности частоты задающего СВЧ генератора на выходные параметры допплеровских РЛС непрерывного излучения, ч. 1, «Электронная техника», сер. 1, Электроника СВЧ, 1966, вып. 12, стр. 119—131, ч. II, «Электронная техника», сер. 1, Электроника СВЧ, 1967, вып. 1, стр. 96.

63. Рейвен. Требования к опорным генераторам для когерентных радиолокационных станций. ТИИЭР, 1966, т. 54, № 2, стр. 150.

Page 197.

64. Багдади, Линкольн, Нелин. Кратковременная стабильность частоты: определения, теория и измерения. ТИИЭР, 1965, т. 53, № 7.

65. Черепнин Н. В. Основы очистки, обезгаживания и откачки в вакуумной технике. Изд-во «Советское радио», 1967.

66. Champeix R., Huber H. La technologie en service de la fiabilité des tubes électroniques. L'onde electrique, 1963, № 438, septembre.

67. Патент Англии № 874.727, 1961, кл. 39(1).

68. Бродуленко И. И. и др. Релаксационные флюктуации выходного сигнала в клистронах малой мощности. «Электронная техника», сер. 1, Электроника СВЧ. 1971. вып. 4, стр. 106—116.

69. Патент США 2.996.639 от 15/VIII 1961, кл. 315-5.19.

70. Патент Англии 867.021 от 3/V 1961, кл. 39(1).

71. Бычков С. И., Буренин Н. И., Сафаров Р. Т. Стабилизация частоты генераторов СВЧ. Изд-во «Советское радио», 1962.

72. Капланов М. Р., Левин В. А. Автоматическая подстройка частоты. «Госэнергоиздат», 1962.

73. Берштейн И. Л. Флуктуации частоты генератора при применении схем автоматической стабилизации частоты. «Известия вузов», сер. Радиофизика, 1964, т. VII, № 2, стр. 328.

74. Чепига В. П. Стабильность частоты клистронных генераторов в различных системах стабилизации. «Вопросы радиоэлектроники», сер. 1, Электроника, 1962, в. 4, стр. 38.

75. Зырин С. С., Кузнецов Ю. Н., Пителин А. П. К расчету коэффициента стабилизации частоты отражательного клистрона в системе связанных резонаторов. «Вопросы радиоэлектроники», сер. 1, Электроника, 1965, вып. 11, стр. 18.

76. Кузнецов Ю. Н., Пителин А. П. Потери мощности и устойчивость рабочей частоты при стабилизации отражательного клистрона в системе связанных резонаторов. «Вопросы радиоэлектроники», сер. 1, Электроника, 1959, вып. 11.

77. Magid M. Broad — band frequency stabilization of a reflex klystron by means of external high-Q cavity. „IRE National Convention Record", 1957, P. 1, p. 208.

78. Уткин Г. М., Хрюнов А. В. Стабилизация частоты отражательного клистрона при помощи высокодобротного резонатора. «Радиотехника и электроника», 1962, т. 7, № 3.

79. Rabinowitz S. J. Stabilization of reflex klystrons by high-Q external cavities. Trans. IRE, 1954, v. MTT-2, № 3, p. 23.

80. Кузнецов Ю. Н., Парышкуро Л. А. Стабилизация частоты клистронного генератора дополнительным объемным резонатором высокой добротности. «Вопросы радиоэлектроники», сер. 1, Электроника, 1960, вып. 3, стр. 77.

81. Петров Д. М., Пителин А. П. Расчет отражательного клистрона на заданную стабильность частоты. «Электронная техника», сер. 1, Электроника СВЧ, 1966, вып. 7, стр. 18.

82. Кузнецов Ю. Н., Петров Д. М., Пителин А. П. Перестройка частоты отражательного клистрона стабилизирующим резонатором. «Электронная техника», сер. 1, Электроника СВЧ, 1966, вып. 8.

83. Половков И. П. Стабилизация частоты генераторов СВЧ внешним объемным резонатором. Изд-во «Советское радио», 1967.

84. Голант М. Б., Каплун З. Ф. Расчет рабочей полосы клистронного генератора, стабилизированного высокодобротным резонатором. «Электронная техника», сер. 1, Электроника СВЧ, 1969, вып. 4, стр. 3.

85. Голант М. Б., Захарова А. Н., Каплун З. Ф., Шаталова Н. В., Фролов А. Г. Вычисление полос удержания и захвата стабилизированного отражательного клистрона. «Электронная техника», сер. 1, Электроника СВЧ, 1969, вып. 7, стр. 19.

86. Кузнецов Ю. Н. Конструкция герметизированного стабилизирующего резонатора. «Вопросы радиоэлектроники», сер. 1, Электроника, 1964, вып. 4, стр. 79.

87. Котырев Е. А. Задающий генератор СВЧ на усилительном клистроне. «Вопросы радиоэлектроники», серия общетехническая, 1964, вып. 24, стр. 30.

88. Савшинский В. А. Флуктуации колебаний в генераторе на пролетном клистроне с высокодобротным резонатором в цепи обратной связи. «Вопросы радиоэлектроники», сер. 1, Электроника, 1965, вып. 9.

89. Царапкин Д. П., Оксинойд К. Э. Сравнение двух схем стабилизации частоты автогенераторов на пролетном клистроне внешним резонатором. «Доклады научно-технической конференции по итогам научно-исследовательских работ за 1966—67 гг.» (секция радиотехническая, подсекция теории колебаний). Изд. МЭИ, 1967, стр. 144.

90. Царапкин Д. П., Оксинойд К. Э. Исследование автогенератора с затягиванием на пролетном клистроне. «Доклады научно-технической конференции по итогам научно-исследовательских работ за 1966—67 гг.» (секция радиотехническая, подсекция теории колебаний). Изд. МЭИ, 1967, стр. 135.

91. Каплун З. Ф. Использование сверхпроводимости в электронике СВЧ (обзор). «Электронная техника», сер. 1, Электроника СВЧ, 1970, вып. 7, стр. 3.

92. Голант М. Б., Каплун З. Ф., Дедик Ю. В., Иваницкий К. П. Клистронный генератор трехсантиметрового диапазона, стабилизированный сверхпроводящим резонатором. «Приборы и техника эксперимента», 1969, № 3.

93. Whale A. V. A klystron oscillator having low frequency modulation siedeband noise. Tubes pour hyperfrequences. Travaux du Congrés international, Paris, 1964.

94. Jonson S., Smith B., Calder D. Noise spectrum characteristics of low — noise microwave tubes and solid — state devices. Proc. IEEE, 1966, v. 54, № 2, p. 258—265.

95. Feehan J. D. Reflex klystron or solid-state-when do you use which source? Electr. Design., 1965, September, p. 28—35.

96. „Varian", Electron tubes, solid state devices, components, catalog № 13, 1969.

97. Hamilton J. J. Low-noise C-W klystron oscillators meet doppler radar requirements. Electronics, 1963, № 49, p. 85—87.

98. Малошумящий клистрон, перестраиваемый одной ручкой (реклама фирмы «Varian»). «Электроника», 1966, № 7, стр. 77—78.

99. Лопин М. И., Новоселец В. И. К расчету стабильного малошумящего клистронного генератора, «Электронная техника», сер. 1, Электроника СВЧ, 1969, вып. 1, стр. 21.

100. Searles C. B. An ultra-low-noise X-band signal source. IEEE Trans., v. ED-16, 1969, № 2, p. 91.

101. Голант М. Б., Маклаков А. А., Шур М. Б. Изготовление резонаторов и замедляющих систем электронных приборов. Изд-во «Советское радио», 1969.

102. Анищенко В. С., Соколов И. П., Штыров А. М. Влияние плотности тока на шумность электронного пучка, «Электронная техника», сер. 1, Электроника СВЧ, 1969, вып. 11, стр. 111.

103. Bell D. A. Electrical noise. Fundamentals and physical mechanism. London, 1960.

104. Ананьев И. В. Справочник по расчету собственных колебаний упругих систем. ОГИЗ, 1946.

105. Рабодзей Н. В. К расчету конструкций электровакуумных приборов на устойчивость при вибрации. «Вопросы радиоэлектроники», сер. 1, Электроника, 1959, вып. 3, стр. 128—139.

END

DTIC

8-86